ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: AZ-SP-9301

PAVEMENT NETWORK OPTIMIZATION AND IMPLEMENTATION

Special Report

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February 1993

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catatlog No.
AZ-SP-9301		

4. Title and Subtitle	5. Report Date
PAVEMENT NETWORK OPTIMIZATION AND IMPLEMENTATION	FEBRUARY 1993
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Kelvin C. P. Wang, John Zaniewski, George Way, and James Delton	
9. Performing Organization Name and Address	10. Work Unit No.
Arizona Department of Transportation 206 South 17th Avenue Phoenix, Arizona 85007 Center for Advanced Transportation System Research Arizona State University Tempe, Arizona 85287-5306	
	11. Contact or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report & Period Covered
ARIZONA DEPARTMENT OF TRANSPORTATION 206 S. 17TH AVENUE PHOENIX, ARIZONA 85007	FINAL 1991-92
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The purpose of this project was to enhance the award winning ADOT Network Optimization System, NOS, and implement the entire NOS in the microcomputer environment.

Extensive revisions were made to the original NOS model. The factor of cracking change, in the existing NOS, was determined to be not significant in predicting pavement deterioration. It was also revealed that the effective number of rehabilitation actions is 6 rather than the 17 used in the original system. The levels of classifications for the existing roughness and cracking were adjusted to reflect the current pavement condition.

New transition probability matrices, TPM'S, were generated based on the pavement performance data base. Pavement Probabilistic Behavior Curves, P.B.C., were established for the analysis of pavement long-term behavior based on Chapman-Komolgorov equations. Accessibility rules were established to ensure that pavements can only stay in their current condition or deteriorate to worse condition under routine maintenance. As a result, a new structure of NOS was set up using 45 condition states and 6 rehabilitation actions. Extensive sensitivity analysis was conducted with the new NOS through the use of a newly developed 32-bit linear optimizer NOSLIP.

It was determined that the reduction of the problem size improves the effectiveness of NOS. More importantly, past pavement behavior was compared against the Markovain prediction based on the new TPM's with satisfactory results. It was concluded that steady state results should not be used for determining the pavement preservation program. The microcomputer based NOS improves the reliability and ease of use of NOS for the network preservation program.

17. Key Words	18. Distribution Statement	23. Registrant's Seal
Pavement Management System, Linear Optimization, Probabilistic Behavior of Pavements, Microcomputer Applications, Network Optimization System, Highway Preservation	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161	10009 GEORGE B. WAY 3/8/93 ARIZONA, U.S.A.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	200	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

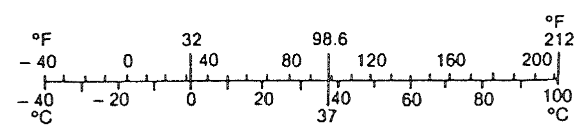
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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Computer Disk Availability

The software package of NOS for the IBM OS/2 2.0 environment is available by written request. Please write to the following address for the shipment of the package.

The 32-bit Linear Optimizer, NOSLIP, is included in the kwnos.exe file of the microcomputer based NOS. The IBM OS/2 2.0 or newer version has to be installed in the computer before running NOS. It is strongly recommended that a high-end 486 computer or better with minimum of 16 megabytes of RAM and 50 megabytes of free hard drive space be used as the hardware platform, although a 386 with a math co-processor is operational with the NOS.

Computer speed and the RAM size are the two main factors determining the feasibility for NOS to conduct long-term analysis in OS/2 2.0. A 20-year NOS run was successfully conducted on the 50-MHz 486 with 24 megabytes of RAM with a high speed 32-bit SCSI hard drive controller. Any NOS runs for less than 10-year analysis period can be conducted in a reasonable time on a high speed microcomputer.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Federal, state and local highway agencies are facing greater challenges in the 1990's than ever before in preserving the vast investment in the nation's highways. These agencies have to deal with the problems related to rising costs, reduced resources, increased utilization of the pavements, and budget needs that exceed revenues. In addition, the emphasis on highway investment has changed from construction to rehabilitation of existing highway networks. Therefore, the preservation of the pavements within the highway network requires cost-effective decisions based on sound management and engineering. A well-designed pavement management system, PMS, can help upper management or decision-makers to make decisions maximizing the effectiveness of every dollar available for the preservation of pavements.

In the mid-1960's, project management research found a system approach which is useful in selecting cost-effective procedures to preserve individual or site specific projects (Hudson, et al. 1979). In the 1970's these project management procedures were expanded to the network evaluation and management.

As defined in National Cooperative Highway Research Program (Hudson, et al. 1979), a pavement management system, PMS, is a set of tools or methods that assist decision-makers in finding the optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time. The function of a PMS is to improve the efficiency of decision-making, expand its scope, provide feedback on the consequences of decisions, facilitate the coordination of activities within the agency, and ensure the consistency of decisions made at different management levels within the same organization. A more recent definition by the Federal Highway Administration, FHWA, outlines a PMS as a set of tools or methods that can assist decision-makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in a serviceable condition (AASHTO PMS Guide 1990). A more pragmatic description of a PMS is that it will help make decisions relative to what rehabilitation actions are the most cost-effective, where the actions are needed and when are the best times to implement the actions.

The products and information that can be obtained and used from a PMS include planning, budgeting, scheduling, performance evaluation and research, and are summarized as follows (AASHTO PMS Guide 1990):

1. An inventory of pavements in the network by location, type, functional classification, mileage, pavement area, etc. A comprehensive database relative to pavement condition, accidents, traffic, construction, maintenance and rehabilitation histories, etc. The current and projected conditions of the pavement network, as a function of the funds available.

2. The budgets required to bring the total network from its current condition to desired condition levels and to maintain network at specified levels of performance for multiple years, i.e. 5 to 20. Methods for prioritizing expenditures when funding is less than required to meet specific performance objectives. Specify programs for single or multi-year planning horizons.

3. Bases for communication between groups within an agency; e.g. planning, design, construction and maintenance and between groups outside an agency; e.g. legislature, local governments, media, public interest group, etc.

4. A basis for comparing alternate preservation strategies for maintenance, rehabilitation and re-construction, MR&R, of pavements in the network.

Two major levels of pavement management decision are included in a PMS: network and project. Network-level decisions are concerned with programmatic and policy issues for an entire network, which include: establishing pavement preservation policies, identifying priorities, estimating funding needs, and allocating budgets for MR&R. Project level decisions address engineering and technical aspects of pavement management, i.e. the selection of site-specific MR&R actions for individual project or group of projects. Figure 1.1 (AASHTO 1990) shows a schematic representation of the three typical modules of a PMS. The first module is a database which contains the data for PMS analysis. The second module is analysis methods to generate products useful for decision-making. The third module is a feedback process which uses on-going field observations to improve the reliability of PMS analysis.

The main choices for the analysis method, in increasing order of sophistication, are: pavement condition analysis, priority assessment models, and network optimization models. Pavement condition analysis combines the pavement condition data for individual distress types, with or without roughness, into a score or index representing the overall pavement condition. The outputs from this module can include:

1. ranking of all pavement segments according to types of distress and condition scores as a function of traffic or road classification,

2. identification of MR&R strategies, which define a set of criteria for assigning a particular action to each pavement segment, and

3. estimates of funding needs for the selected treatments.

A prediction model is not used in this module, as pavement condition analysis addresses only the current states of the network.

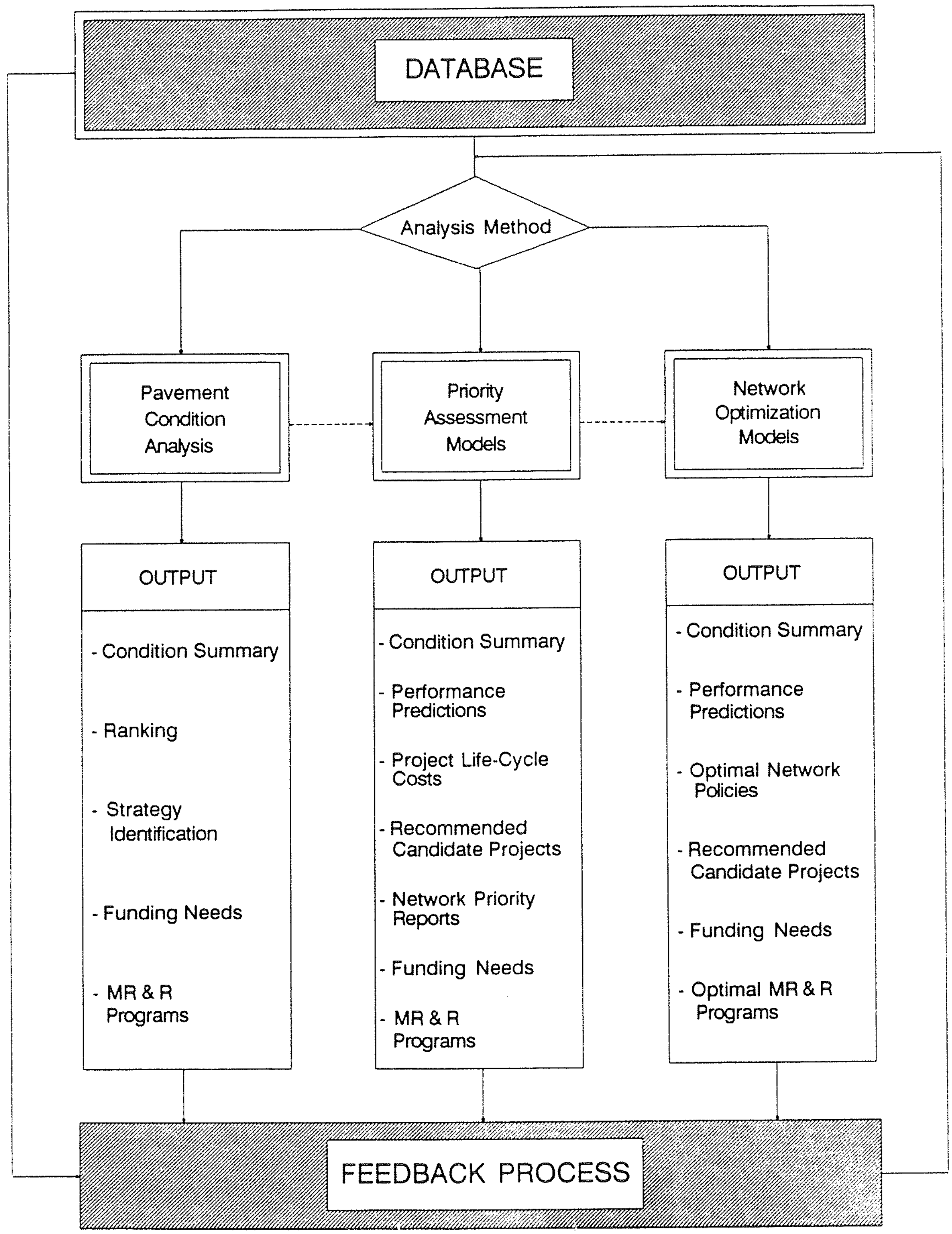


FIG. 1.1. A Schematic Representation of PMS Modules (AASHTO Guideline for Pavement Management Systems, 1990)

Priority Assessment Models use a "bottom up" approach in which MR&R strategies for individual projects are first determined based on life-cycle costs over the analysis period of 20-30 years for at least one major rehabilitation action. Projects can be prioritized at the network level by using methods such as benefit/cost ratio or measurement of cost-effectiveness. The project-level analysis includes models to predict pavement conditions as a function of such variables as age, present pavement condition, traffic, environment, performance history, and the action selected. Alternate strategies, including current and future actions, are evaluated for each segment and compared based on life-cycle cost analysis, benefit/cost ratio or cost-effectiveness. The strategy with the highest priority over an analysis period is identified. The output from this method includes:

1. a prioritized listing of projects requiring maintenance, rehabilitation or reconstruction,
2. costs for MR&R treatments,
3. estimates for funding needs in order to achieve specified network performance standards, and
4. single-year and multi-year programs which identify segments recommended for maintenance rehabilitation or reconstruction, and the type, timing and cost of recommended actions.

Optimization models provide the capability for a simultaneous evaluation of the entire pavement network for a multi-year horizon at specified condition standards for each year. The objective is to identify the network MR&R strategies which maximize the total network benefits (or performance), or minimize total network costs subject to network-level constraints such as available budget and desired performance standards. A network MR&R strategy defines the optimal action for each possible combination of performance variables such as roughness, distress, traffic, environment, and functional class. The structure of outputs from optimization models is similar to that obtained from prioritizing model. However, optimization allows not only tradeoffs among projects in selecting strategies, but also is capable of evaluating large number of strategy combinations for any project in order to achieve maximum benefit or minimum cost. Nevertheless, the current optimization models do not identify segment priorities, rather, it selects an optimally balanced MR&R program for an entire network to meet specified budget and policy constraints.

1.2 PROBLEM STATEMENT

Extensive research has been conducted in the last 20 years in the area of network-level PMS. The methodologies used in PMS have been evolving along with the advancement of new technologies in computer science and mathematical modeling. The early efforts in implementing network level PMS were discussed in Federal Highway Administration (1983). Compared to other major industries, such as manufacturing, the pace of adopting new techniques for PMS in the highway departments is relatively slow, and the scale of implementing such techniques is limited.

In the early 1980's, a major PMS development occurred in the Arizona Department of Transportation, ADOT, which represented the pioneering efforts of applying Operations Research techniques in PMS, specifically, techniques of the stochastic theory and optimization method (Kulkarni et al. 1980). The system methodology used in ADOT PMS is called Network Optimization System, NOS. It uses a Markov process to define the transitions of pavement conditions and a linear programming model to minimize the total agency cost and maintain the highway network at specified standards for a multi-year horizon. Subsequently, a national Management Science Achievement was awarded to ADOT and the NOS developer Woodward-Clyde Consultants (Golabi et al. 1982).

However, there are a few problems associated with NOS that have hindered its wide acceptance as a major PMS methodology by highway agencies. First, no major update to the core methodology of NOS, nor the basic data analysis tools, were developed in the last ten years. The complexity and sophistication of NOS was not appealing to many highway agencies. Very limited literature was available to interpret and promote the system so that the general pavement engineering community can accept the concepts used in NOS. Second, NOS is an excellent tool for conducting financial planning for the network preservation program. But, the project selection process in the existing NOS is primitive and rarely used for the actual project programming by ADOT. Third, the mainframe implementation of NOS requires excessive resources by today's standards. For example, considerable effort is required to maintain and update the input databases for NOS. New technologies in the micro computing area have provided opportunities to conduct these tasks more readily, and more efficiently.

Therefore, there was a need for developing a new NOS which should provide the virtues of having better data analysis tools, having a practical project selection process, being easier to use, and having better accessibility.

1.3 RESEARCH GOAL AND METHODOLOGY

The goal of this study was to develop an enhanced, micro-computer based Network Optimization System by applying techniques in Operations Research, and new software technologies.

The specific objectives of this research are:

1. review the existing NOS as used in ADOT and make necessary changes to the structure of the model,
2. generate new transition probability matrices, TPM's, based on the real pavement performance database in order to improve the reliability of pavement performance prediction, as opposed to the existing regression equation based TPM's,
3. conduct long-term pavement probabilistic behavior analysis based on TPM's and the Chapman-Kolmogorov equations,

4. develop a 32-bit micro-computer based NOS, which includes an optimizer for linear programming, matrix generation, and report writing, and
5. conduct sensitivity analysis of the new NOS on the variations of rehabilitation costs and performance standards.

1.4 OVERVIEW OF THE STUDY

An enhanced network optimization system, NOS, was implemented in the microcomputer environment in this study. The capabilities of the new NOS match these of the mainframe version. Enhancements were made to the model structure and new analysis tools were provided for pavement management.

In Chapter 2, a comprehensive review was conducted of the ADOT pavement management system. The development of the original NOS was presented through detailed interpretation of pavement transition process and the original development of transition probability matrices. This chapter also covers the Arizona Markovain prediction model and the NOS model set up.

Changes to the original NOS model were necessary to improve the reliability of the model as presented in Chapter 3. The structure of the original NOS was modified to more realistically model pavement performance in Arizona. The Chapman-Kolmogorov equations were used as the important analysis tool for this modification. New transition probability matrices were generated for the new NOS structure based on real pavement performance data.

The implementation of the enhanced NOS in the micro-computer environment is documented in Chapter 4. A native 32-bit linear optimizer developed for NOS was used for this implementation. Extensive validation tests and sensitive analysis were conducted for the new NOS.

Finally, Chapter 5 presents the conclusion and recommendations from this study.

CHAPTER 2

OVERVIEW OF THE PAVEMENT MANAGEMENT SYSTEM FOR THE ARIZONA DEPARTMENT OF TRANSPORTATION

2.1 INTRODUCTION

The highway network in Arizona represents at least 10 billion dollars investment (Way, 1985). As the interstate system in Arizona neared completion in the mid 1970's, it was apparent that the emphasis would shift from building new highways to preserving the existing roads. The management of Arizona Department of Transportation, ADOT, recognized the need for an objective, systematic and rational method of preserving the enormous investment.

The highway budget of ADOT is divided into four categories: construction, pavement preservation, maintenance, and operations. ADOT pavement management system addresses budget programming for pavement preservation and maintenance. In 1979 ADOT selected Woodward-Clyde Consultants, WCC, to develop an optimization-based program for the state highway network (Kulkarni et al. 1980). The result of the research project was the Network Optimization System, NOS (Golabi et al. 1982) for programming and budgeting of highway preservation needs. This system uses a true optimization procedure that is unique among the existing pavement management systems. It represented a significant advancement in applying techniques in systems engineering and Operations Research to Pavement Management. The basic model of NOS has been used by Alaska DOT, Kansas DOT (FHWA 1991), Finland (Thompson, et al. 1987), and Saudi Arabia (Harper, et al. 1991).

NOS was implemented in 1980 in ADOT and was recognized nationally in 1982. It has been used since then to develop the annual preservation budget and schedule of projects. Estimated 40 million dollars were saved for the State of Arizona from 1980 to 1985 (Way, 1985).

2.2 THE ADOT PAVEMENT MANAGEMENT DATABASE

The Arizona PMS includes data collection, storage and retrieval in addition to the NOS. ADOT annually surveys each mile of the state highway system for ride roughness, cracking, flushing and patching. In addition, rut depth measurements are taken annually on all interstate highways. Skid resistance measurements are taken on a priority basis, with special requests given priority, whereas routine inventory tests are conducted as time permits. The collected data are made available to the pavement design personnel and engineers involved in the five-year pavement preservation program through a carefully designed pavement management database.

2.2.1 Data Collection

One of the major criteria of measuring roadway adequacy is the comfortable and safe ride it provides the traveling public. The equipment used by ADOT to measure road roughness is the Mays Ride Meter. It measures the movement between the rear axle and the body of the car in response to pavement roughness. The meter is mounted in a full-size car equipped with coil springs, firm shock absorbers, and front and rear anti-roll bars. Axle movement relative to the body is measured in one tenth of an inch increments (counts) by the transmitter that is rigidly mounted in the trunk directly above the axle. The roughness counts are stored in computer disks as the accumulated counts and the distance traveled during the test.

The count from the transmitter are converted to inches per mile by dividing the total roughness counts by the distance over which they were measured, usually 1 mile. These results are adjusted by the calibration for the specific vehicle. The final results are used for the analysis of roadway roughness. They also can be converted to a serviceability index SI by the following equation (ADOT, 1989):

$$SI = 0.3488 + 4.6836 \cdot 0.9970^{R} \qquad \text{......(2.1)}$$

Where:

R is the Maysmeter value.

Recently ADOT purchased a KJ LAW profilometer model 690 with the state of the art technology for measuring surface roughness. As a result of this effort and others, ADOT has converted all of the existing historical Mays-meter data to calibrated Mays-meter data in accordance with the standard methods (Gillespie, et al. 1980). Therefore, The SI equation is modified as follows (ADOT, 1989):

$$SI = 0.3488 + 4.6836 \cdot 0.9970^{(R-4.255)/0.54} \qquad \text{......(2.2)}$$

Where:

R is the calibrated Maysmeter value.

The amount of cracking of the pavement is recorded as a percentage of a 1000 square foot area at each mile post. Patching is defined as any repair or replaced area or a surface treatment placed by maintenance forces. The amount of patching is recorded as a percent of area. It is usually found in small isolated spots but can occasionally be seen over the entire width of the roadway for a hundred feet or more. Flushing results from an excess of asphalt on the surface of the pavement. It is recorded as a severity rating from 1, severe and bleeding, to 5, no flushing. Rut depth is defined as the mean depth of a rut in the wheel paths , measured with a four foot straight edge.

One important characteristic of a pavement is surface friction which effects the skid resistance the pavement provides. Collection of friction data is conducted dependent on the availability of manpower after condition survey and roughness surveys are accommodated. The device used by ADOT to determine surface friction is the Mu-meter, a continuous recording friction measuring trailer. It measures the side-force friction generated between the test surface and two pneumatic tires which are each set at a fixed toe-out angle of 7-1/2 degrees. The frictional force is sensed by a transducer located near the apex of the trailer's frame. During the test, water is sprayed under the test tires to simulate wet pavement conditions. Tests are generally made for 500 feet and inventory tests normally begin at the mile post.

2.2.2 Data Storage

The pavement management database contains a record for each milepost of two lane roads in the state and a record for each mile post in each direction for divided highways. There are a total of 7498 records, or sections, in the system. The fields in the data base contain location descriptors, pavement condition variables and historical information on traffic and maintenance. The pavement condition data include fields on the roughness, cracking, patching, rutting, flushing, skid resistance. Each record contains the complete condition history of the section dating back to the time when the data were first collected. The roughness data are collected with a Maysmeter and date back to 1972. The cracking data are estimates of the percent of the surface cracked and date back to 1979. The data of rutting, patching and flushing date from 1986, 1979, and 1979 respectively. The maintenance information includes fields for the most recent type of maintenance or rehabilitation project on the section. All the data are stored in a dBase III file and the file format is shown in Figure 2.1. Based on these collected data, guidelines are established in ADOT for categorizing pavements as shown in Table 2.1.

2.3 METHODOLOGIES FOR THE NETWORK OPTIMIZATION SYSTEM, NOS

The Network Optimization System, NOS, uses an optimization method for minimizing the overall costs of maintaining the highway network to a set of specified standards over a number of years (five years in ADOT implementation) planning period. The major features of the optimization process are the road categories, current condition of the pavements, transition probability matrices, rehabilitation costs, infeasible actions, and condition standards. The output of the NOS is for each road category, the percent of pavements in each condition state that should receive a specified rehabilitation action.

The overall NOS methodology contains the following components:

- selection of functional criteria and performance variables,
- selection of influence variables for each performance variable,
- selection of road categories and condition states,
- specification of rehabilitation actions and policies, and
- development of the optimization model.

TABLE 2.1. Pavement Classification for ADOT

FACTORS	LEVELS	LEVEL CUTOFF
Roughness	Satisfactory	0 - 93 in/mile
	Tolerable	94 - 142 in/mile
	Objectionable	> 142 in/mile
Percent Cracking	Low	< 10
	Medium	10 - 30
	High	> 30
Mu-meter Number	High	43 - 99
	Medium	35 - 42
	Low	< 35
Average Daily Traffic (ADT)	Low	501-2000
	Medium	2001 - 10,000
	High	> 10,000
Traffic - 10 Year Cumulative 18 KIP Single Axle Equivalent Loads (EASL'S)	Low	0 - 50,000
	Medium	51,000 - 375,000
	High	376,000 - 1,250,000
	Very High	> 1,250,000
Seasonal Variation Factor	Low	Desert: 0 - 1.7
	Medium	Transition: 1.8 - 2.7
	High	Mountains: > 2.7
Annual Maintenance Cost ($ Per Lane mile)	Low	0 - 333
	Medium	334 - 666
	High	> 666

FIELD NAMES	A	RTNO	D	MP	L	PW	LS	RS	DIST	AREA	REG	ADT	ADL	
DATA RECORDS	I	8	E	1	2	24	4	10	3	7	0.4	11915	1247	->
	I	8	E	2	2	24	4	10	3	7	0.4	11915	1247	->
	...	...	...	...	...	...	...	...	...	...	...	...	...	->
	U	666Y	E	89	2	24	5	5	2	4	1.9	167	16	->
	U	666Y	E	90	2	24	5	5	2	4	1.9	167	16	->

GF	C79	...	C91	R72	...	R91	M72	...	M91	RUT86	...	RUT91	P79	...	P91	
4.3	0	...	4	x	...	45	x	...	x	0.12	...	0.25	0	...	0	->
4.3	0	...	9	x	...	60	x	...	x	0.29	...	0.3	0	...	0	->
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	->
1	5	...	10	x	...	87	x	...	x	x	...	0.2	0	...	0	->
1	3	...	0	x	...	71	x	...	x	x	...	0.1	0	...	0	->

F79	...	F91	MC_79	...	MC_91	SN	PROJECT	YR	LAYER INFOR	RATE	FY
5	...	4.5	4	...	61	3	IIG 8- 1- 62	77	x	14.4	x
4.5	...	3.5	1412	...	2991	3	IIG 8- 1- 62	77	x	22.4	x
...	...	...	...	...	...	...	...	...	...	...	...
5	...	4.5	0	...	0	2.96	S207- - 12	61	x	22.2	x
5	...	4.5	0	...	0	2.96	S207- - 12	61	x	10.7	x

Notes:

->: Continue;

"x" indicates the value in the particular cell is not available.

Field Name Designations:

- Functional Classification, I=Interstate, S=State Highway, U=US Highway;
- RTNO, D, MP, L: Route Number, Direction, Milepost and Number of Lanes respectively;
- PW, LS, RS: Number of Lanes, Pavement width, Left shoulder width and Right shoulder width respectively;
- DIST, AREA, REG: District Number, Engineering Area, Regional Factor respectively;
- ADT, ADL, GF: Average Daily Traffic, Average Daily Load and Traffic Growth Factor respectively;
- Ci, Ri, Mi, RUTi, Pi, Fi, M_Ci: Cracking, Roughness, Mu Meter Number, Rutting, Patching, Flushing, Maintenance Cost in year i respectively;
- SN: AASHTO Structural Number;
- Project, YR, LAYER INFOR, RATE, FY: The Information for the Latest Project;

FIG. 2.1. Data Format of the Pavement Management Database for ADOT

2.3.1 Functional Criteria and Performance Variables

Functional criteria address the broad areas of concern (e.g. safety, user comfort, and physical distress) that are relevant to the determination of the acceptability of pavement performance. Performance variables are measures of the degree to which the performance of a pavement meets various functional criteria. Examples of functional criteria are shown in Table 2.2.

Rutting, excess user costs due to traffic delay and vehicle operating costs are not used in NOS as performance variables. It is usually difficult to predict rutting in quantitative terms. In addition, it was not a significant problem in Arizona when the system was developed. User costs, or "excess" user costs are associated with increased vehicle operating costs from pavement roughness or traffic delays caused by high roughness levels or rehabilitation activities. Previous experience indicates that excess user costs, particularly costs related to pavement roughness, will dominate the rehabilitation and design strategies (Kulkarni, et al 1980). The resulting policy requires higher performance standards, that are more expensive to the highway agency when compared with analyses that do not include user costs a analysis factor. For example, the majority of traffic volume in Arizona is in the Phoenix metro area, if user costs are considered, extensive rehabilitation work has to be conducted to keep the metro highway network in almost pristine condition to minimize vehicle operating and traffic delay costs. Furthermore, it is difficult, if not impossible, to quantify the benefits of reducing user costs so that a convincing presentation can be given to the legislature in order to solicit higher budgets. Clearly, this is not an acceptable policy for an agency which must serve the entire state.

However, user costs are indirectly and partially considered in the current NOS model by applying pavements roughness standards as constraints for the system, as roughness is the important parameter in estimating vehicle operating costs. As an investment institution, HDM-III from World Bank uses user costs as one of the parameters in estimating benefits to the society (World Bank 1985). Also, Zaniewski, et al. (1981, 1985) provided methodologies in calculating and allocating user costs.

Skid number is not included in NOS. It is because pavements with safety deficiencies will be scheduled for rehabilitation under safety projects that are funded separately and are not part of the preservation budget. Therefore, the final performance variables for NOS were roughness and amount of cracking.

2.3.2 Influence Variables for Each Performance Variable

Influence variables are the factors that affect the pavement behavior over time. Table 2.3 shows a list of the influence variables relevant to the prediction of pavement roughness and cracking. However, in order to keep the size of the NOS within manageable limits, it was necessary to limit the total number of influence variables to no more than 4. The more significant influence variables for each performance

TABLE 2.2. Examples of Functional Criteria and Performance Variables

Functional Criteria	Performance Variables
Safety	Skid Number, Rutting
Serviceability	Ride Index
User Convenience	Traffic Delays
User Economy	Excess User Cost
Physical Distress	Amount of Cracking

TABLE 2.3. Examples of Influence Variables for Predicting Pavement Roughness and Amount of Cracking

Present Roughness, Present Amount of Cracking
Deflection, Spreadibility
Traffic Volume, Equivalent 18 kip Single Axle Loads
Age, Environment, Drainage
Structural Number, Thickness of Surface Layer

TABLE 2.4. The Influence Variables used in the Regression Equations

Rate of Change in the Performance Variable	Influence Variables
Pavement Roughness	Present Roughness
	Regional Factor
	Rehabilitation Action
Amount of Cracking	Present Amount of Cracking
	Change of Cracking from the Previous Year
	Regional Factor
	Rehabilitation Action

variable were determined using regression analysis of sample pavement performance data collected by ADOT (Kulkarni, et al. 1980). As the prediction of rates of change in performance variables were needed to forecast pavement performance, the influence variables included in the final regression equations are shown in Table 2.4.

The regional factor was an AASHO regional factor adjusted for the environmental conditions in Arizona. Elevation and rainfall were the primary variables used to define the regional factor on a scale of 0 to 5. The smaller numbers on the scale indicate lower elevations with relatively small amount of rainfall.

Traditional influence variables (such as deflection, spreadibility, traffic, AC thickness) were not included because they did not show a significant correlation with the dependent variable. However, the influence of such conventional variables were indirectly included through the pavement condition variables.

The main effect of different types of rehabilitation actions is on the time of crack initiation (first visible crack). For example, a thick overlay will be crack-free longer than a thin overlay. To incorporate this effect, the variable "index to first crack" was used to indicate the range of years to the first crack. Past data and engineering judgment were used to estimate the number of years to the first crack for different rehabilitation actions. The index to first crack is also a function of ADT and regional factor.

The set of variables that were determined to be relevant to evaluating pavement performance in NOS is used to classify road categories and pavement condition states and includes the following:

- Functional Class (Interstates or Non-interstates),
- Average Daily Traffic (ADT),
- Regional Factor,
- Index to First Crack,
- Present Roughness,
- Present Amount of Cracking,
- Change in Amount of Cracking during the Previous Year.

2.3.3 Road Categories

The first three variables in the above set can be considered to be independent of the rehabilitation actions applied to a pavement, i.e. the functional class, the ADT and regional factors are assumed to be fixed for a given pavement. Combinations of different levels of these two variables and the functional class of highways were termed road categories which are defined by:

- functional class - Interstate and non-interstate,
- traffic level - low, medium and high, and

- region within the state - mountain, transition, and desert.

This produces a total of 18 road categories. However, the low traffic level does not exist for the Interstates thus, the NOS uses 15 road categories. Road categories are treated independently by the NOS optimization procedure. Therefore, the optimization occurs within each road category.

2.3.4 Condition States

The condition of the pavement network is defined in terms of the percent of the network that is in each condition state, defined as the following:

Factor	Levels	Unit
Roughness	<94, 94 - 142, >142	Maysmeter Output, inches/mile
Cracking	<10, 10 - 30, >30	percent of area
Cracking Change	0 - 5, 6 - 15, >16	percent in one year
Index to First Crack	1, 2, 3, 4, 5	N/A

The index to first crack was conceptually an estimate of the time between the construction or rehabilitation of the pavement to occurrence of the first crack. However, this index is used in NOS to select a TPM based on the most recent rehabilitation. There are five levels of the index to first crack based on the type of rehabilitation treatment.

Roughness, cracking and crack change are based on the observed condition of the pavement. There are 27 combinations of these factors. However, the combination of low level crack and high level of crack change in one year is not feasible, resulting in 24 feasible combinations. When the five levels of index to first crack are considered there are 120 combinations as shown in Table 2.5.

Each pavement section in the network is placed into a road category and a condition state to define the characteristics of the population for the optimization process. Once these characteristics have been defined, the NOS operates with the percentages, or fractions, of pavements rather than considering specific pavements sections in the data base. This is an important distinction because it restricts the output of the NOS to generalities rather than specifics, i.e., the NOS can determine the percent of pavements that should be overlaid but not the specific sections of highway that need the treatment. NOS is capable of assigning actions to each mile in the system, however, this feature is not often used for project selection due to the impractical assignment of different actions to each milepost.

TABLE 2.5. CONDITION STATE NUMBERING SYSTEM

R_o	C_o	C_p	INDEX TO FIRST CRACK, I_c				
			INDEX 1	INDEX 2	INDEX 3	INDEX 4	INDEX 5
1	1	1	1	25	49	73	97
1	1	2	2	26	50	74	98
1	2	1	3	27	51	75	99
1	2	2	4	28	52	76	100
1	2	3	5	29	53	77	101
1	3	1	6	30	54	78	102
1	3	2	7	31	55	79	103
1	3	3	8	32	56	80	104
2	1	1	9	33	57	81	105
2	1	2	10	34	58	82	106
2	2	1	11	35	59	83	107
2	2	2	12	36	60	84	108
2	2	3	13	37	61	85	109
2	3	1	14	38	62	86	110
2	3	2	15	39	63	87	111
2	3	3	16	40	64	88	112
3	1	1	17	41	65	89	113
3	1	2	18	42	66	90	114
3	2	1	19	43	67	91	115
3	2	2	20	44	68	92	116
3	2	3	21	45	69	93	117
3	3	1	22	46	70	94	118
3	3	2	23	47	71	95	119
3	3	3	24	48	72	96	120

NOTE:

R_o: Roughness Level;

C_o: Crack Level;

C_p: Crack Change.

2.3.5 Rehabilitation Actions and Costs

The NOS considers 17 rehabilitation actions as given in Table 2.6. The first action is routine maintenance. It is assumed that all pavements that are not selected for a different rehabilitation treatment will receive routine maintenance. The second alternative, seal coat, is a preventive maintenance treatment and will not substantially improve the condition of a deteriorated pavement. The third treatment, asphalt concrete friction course (ACFC), is usually applied to improve skid resistance or roughness, although there will be a reduction in cracking also. The remaining treatments provide structural improvement . There are some differences in the actions available for the interstate and non-interstate roads.

The costs of each of the rehabilitation actions are given in dollars per square yard as shown in Table 2.6. These are updated annually or as needed. In the NOS model, the cost of k^{th} rehabilitation action for a pavement in i^{th} condition state is defined as c(i, k). Except routine maintenance, the costs for all other rehabilitation actions were assumed to be independent of pavement condition states. With respect to routine maintenance costs, a sample of pavements in different conditions were selected and the cost of routine maintenance performed on these pavements were found from the maintenance management system (PECOS) used by ADOT. A regression analysis was conducted to estimate routine maintenance costs as a function of pavement condition. The roughness (equivalent to the ride index) of a pavement and amount of cracking were found to be the main variables that significantly influenced routine maintenance costs. The following equation was developed to calculate ride index as a function of pavement roughness (Kulkarni, et al. 1980):

$$\text{Ride Index} = \begin{cases} 5.0-(0.0155\cdot Roughness)+(0.001\cdot(Roughness)^2/40.96; & \text{if } roughness \leq 192 \\ (100-(0.15625\cdot Roughness))/24; & \text{if } roughness > 192 \end{cases} \qquad \text{......(2.3)}$$

Where:

Roughness was defined as the old Mays-meter number and can be converted to the new Mays-meter number by Roughness = ((New Mays-meter number) - 4.255)/0.54.

The unit of routine maintenance cost is dollars per lane-mile and determined by the following equation :

$$\text{Routine Maintenance Cost} = 950-(200\cdot(rideindex))+(43\cdot(percentcracking)) \qquad \text{......(2.4)}$$

Table 2.7 shows the routine maintenance costs for different rehabilitation actions and pavement conditions.

TABLE 2.6. REHABILITATION ACTION TABLE

	ACTION INTERSTATE	COST $/SY	ACTION NON-INTERSTATE	COST $/SY	I_c INDEX	TO STATES
1	ROUTINE	0	ROUTINE	0	*	1 - 24
2	SEAL COAT	1.19	SEAL COAT	1.20	2	25 - 48
3	ACFC	1.33	ACFC	1.34	2	25 - 48
4	ACFC+AR	4.55	ACFC+AR	4.58	3	49 - 72
5	ACSC	2.59	ACSC	2.61	2	49 - 72
6	AC+AR	8.96	AC+AR	9.02	3	49 - 72
7	2"AC+FC	6.51	2"AC+FC	6.56	4	73 - 96
8	2"AC+AR+FC	8.68	2"AC+AR+FC	8.74	4	73 - 96
9	3"AC+FC	9.10	3"AC+FC	9.17	4	73 - 96
10	3"AC+AR+FC	11.27	3"AC+AR+FC	11.35	4	97 - 120
11	RR(3"TL&2"PL)+FC	5.19	2"AC+SC	6.42	3	97 - 120
12	RR(3"TL&2"PL)+2"	10.44	3"AC+SC	9.02	4	97 - 120
13	RR(4"TL&2"PL)+2"	10.96	RR2"+FC	6.49	4	97 - 120
14	RR(5"TL&3"PL)+2"	11.86	RR3"+FC	8.46	5	1 - 24
15	RR(4"TL&3"PL)+3"	13.83	RR4"+FC	10.43	5	1 - 24
16	4"AC+FC	11.69	4"AC+FC	11.77	5	1 - 24
17	5"AC+FC	14.28	5"AC+FC	14.38	5	1 - 24

NOTE:

AC is Asphalt Concrete;

ACFC is Asphalt Concrete Friction Course;

ACSC is Asphalt Concrete Surface Course;

FC is Friction Course;

AR is Asphalt Rubber;

RR is removal-replace;

TL, PL are traveling lane and passing lane respectively;

The rehabilitation costs were derived based on 1990 data;

I_c is the index to first crack.;

*: I_c in this category depends on the most recent action.

TABLE 2.7. Routine Maintenance Costs based on Rehabilitation Actions and Pavement Conditions

Rehabilitation Action	Present Roughness	Present Amount of Cracking	Routine Maintenance Cost, $/Square Yard
Routine Maintenance	120(±45)	5(±5)	0.066
	"	20(±10)	0.158
	"	45(±15)	0.310
	210(±45)	5(±5)	0.087
	"	20(±10)	0.179
	"	45(±15)	0.332
	300(±45)	5(±5)	0.102
	"	20(±10)	0.193
	"	45(±15)	0.346
Seal Coat	120(±45)		0.036
	210(±45)		0.057
	300(±45)		0.071
All Other Actions			0.036

Note: All costs were based on 1980 terms.

2.3.6 Infeasible Actions

Initial testing of the original NOS demonstrated that rehabilitation action 3, asphalt concrete friction course, was selected a disproportionate amount of the time (Kulkarni, et al. 1980). This was due to the inability of the transition probability matrices to distinguish between the long term performance of the ACFC and structural overlays. Therefore, the input to the program was modified to allow the user to prohibit the consideration of certain actions for certain condition states.

2.3.7 Performance Standards

Performance standards define acceptable levels of pavement condition to meet the needs of the traveling public and are set by management policy. The user of the NOS inputs the minimum percent of sections that should be in good condition and the maximum percent that can be in poor condition for each of the traffic levels for both interstate and non-interstate highways.

The following performance standards were specified:

- The minimum proportion of roads required to be in a state of low roughness and low amount of cracking levels;
- The maximum proportion of roads permitted to be in a state of high roughness and high amount of cracking.

Table 2.8 shows the performance standards for different road categories.

2.4 PAVEMENT PERFORMANCE PREDICTION MODEL

Pavement performance prediction is critical for the period preservation programming needs. The transition pattern of pavement conditions was assumed to be a Markov process (Kulkarni et al. 1980) in the prediction model of NOS.

2.4.1 Transition Probability Matrices, TPM

The performance model used in the NOS is based on transition probability matrices. A transition probability, $p_{ij}(a_k)$, is represented by the proportion of roads in state i that move to state j in one year if the k^{th} rehabilitation action is applied. It defines the probability of transition from one condition state to another in one year under one of the rehabilitation actions, including routine maintenance. The current matrix structure of transition probabilities in NOS consists of 15 road categories, 17 actions (including routine maintenance, seal coat and 15 rehabilitation actions), and 120 states. Total number of matrices is 15 (number of road categories) x 17 (number of rehabilitation actions) = 255.

All pavement sections, within a road category, are placed into one of the 120 condition states. However, since the index to first crack is fixed based on the most recent rehabilitation action, a given

TABLE 2.8. Performance Standards for the Highway Preservation Program of ADOT (Asphalt Concrete)

	TRAFFIC ADT	MIN. % MILES IN SATISFACTORY CONDITION	MAX. % OF MILES IN OBJECTIONABLE CONDITION
INTERSTATE	ROUGHNESS		
	0-2000	NOT APPLICABLE	NOT APPLICABLE
	2001-10,000	90	5
	10,001+	95	1
INTERSTATE	% CRACKING		
	0-2000	NOT APPLICABLE	NOT APPLICABLE
	2001-10,000	80	5
	10,000+	85	1
NON-INTERSTATE	ROUGHNESS		
	0-2000	50	25
	2001-10,000	65	10
	10,000+	80	5
NON-INTERSTATE	% CRACKING		
	0-2000	70	20
	2001-10,000	75	15
	10,000+	80	10

condition state can only transition to one of the 24 condition states associated with the index to first crack in one year under routine maintenance, as shown in Table 2.5.

The concept of the transition between condition states is shown in Figure 2.2. After construction or re-construction, a pavement remains in condition state 1 to 24 until an action other than routine maintenance is applied. Once a non-routine maintenance action is applied, a new index to first crack is defined and the condition state of the pavement is restricted to one of the 24 condition states associated with that index. This structure prohibits a pavement that has received a non-routine maintenance action from entering condition states 1 to 24.

In the year when a non-routine maintenance action is applied, a transition matrix is used to determine the proportion of pavements in each of the 24 condition states associated with the index. Generally one would expect a very high percentage of the pavements would be transformed to the best condition state. For example, Table 2.6 shows the index to first crack is 5 for a 5" overlay with a friction course. Table 2.5 shows the condition states for this index are 97 to 120, with 97 being the best condition state. The probability approaches 1.0 that this treatment would result in a pavement in condition state 97. Seal coat and friction courses generally will hide cracks for one or two years, but seal coat will not improve roughness. These treatments have an index to first crack of 2. The most probable condition states following these treatments are 25, 33, and possibly 41.

In the years after the pavement received a non-routine maintenance treatment, the pavement receives routine maintenance every year until a non-routine maintenance is warranted. Before this happens, the pavement condition will deteriorate within the 24 condition states based on the established transition probability matrix, which was determined according to the latest treatment the pavement received (Figure 2.2). The rate of deterioration is manifested by the value of the transition probability (<1.0) of staying in the best condition state. The bigger the probability, the less the rate of deterioration and vice versa. It is the job of the optimization process to determine the best time to rehabilitate the pavement and what treatment is to be used. This process is conducted by the linear optimizer based on the predicted pavement conditions, the performance standards over time and the cost-effectiveness of individual rehabilitation action. At the same time, the objective to minimize the total agency cost has to be achieved.

The 17 actions were categorized into five groups of index of first crack. Pavements receiving actions within each group have the same transition probability matrix for the period after the actions are applied. The different rates of deterioration for the five groups of rehabilitation actions were determined by using the five transition probability matrices to predict the pavement performance under routine maintenance. Table 2.5 shows a condition state table with all five factors and 120 condition states.

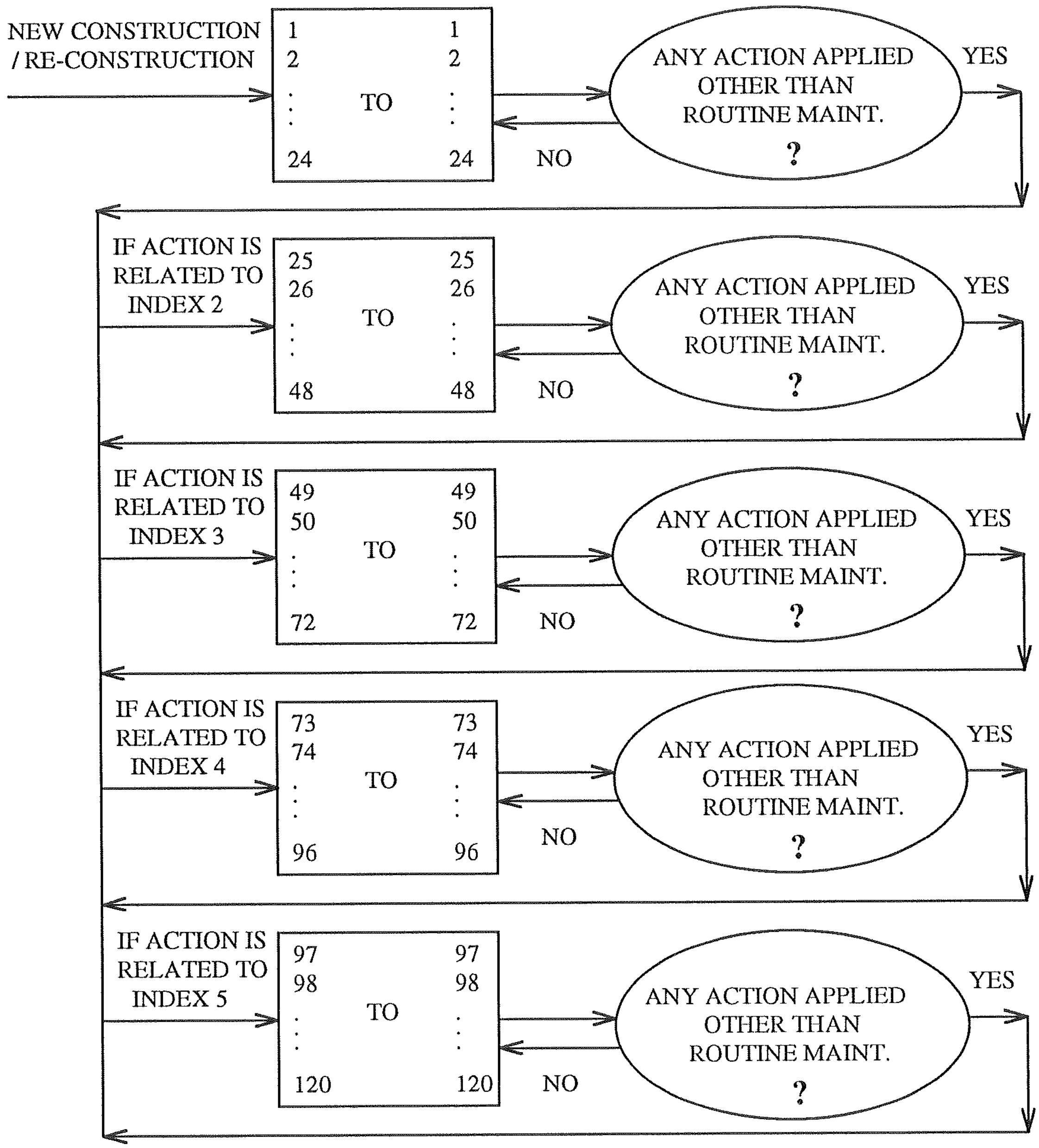


FIG. 2.2. Flow Chart of the Transition Process of Pavement Condition States

In summary, for each of the 15 road categories there is one TPM that is 120 by 120, grouped in five blocks of 24 by 24, for the routine maintenance action. In addition, there are 16 TPM's for the non-routine maintenance actions. These matrices are 120 by 24.

2.4.2 The Development of Transition Probability Matrices, TPM's

The one-step transition probabilities should be calculated directly from pavement performance data. For the development of the NOS, regression equations were determined from a sample of pavement performance data due to inadequate real-world performance data (Way et al. 1980). Transition probability matrices could then be derived from the regression equations of pavement performance. Two sets of regression equations were developed, one for roads which only received routine maintenance and the other is for overlaid roads.

Roughness and cracking are the two performance variables that were included in the NOS. Therefore, four regression equations were generated as follows:

1. Change in roughness under routine maintenance:

$$R_N = -0.125 + 0.138R_0 + 2.65R_G^2 - 0.046R_G \cdot R_0 \qquad \text{......(2.5)}$$

in which:

R_N = changes in roughness in 1 year;

R_o = present roughness

R_G = regional factor.

Summary Statistics:

$R^2 = 0.54$

Standard Error = 10.4

F-Value = 38

2. Change in the amount of cracking of newly constructed roads under routine maintenance:

$$C_N = 0.198 + 0.56C_p + 0.05 \cdot C_p^2 + 0.009R_G^2 + 0.049R_G \cdot C_o - 0.0035C_o^2$$

......(2.6)

in which:

C_N = change in percent cracking in next year

C_p = change in percent cracking in previous year

Summary Statistics:

$R^2 = 0.70$

Standard Error = .64

F-Value = 84

3. Change in roughness following an overlay:

$$R_o^{'} = C_F(R_o - R_N) \qquad ......(2.7)$$

in which:

$R_o^{'}$ = roughness in the end of 1 year following an overlay

C_F = correction factor for special treatment (such as asphalt-rubber)

R_N = difference between R_o and $R_o^{'}$ for an overlay without special treatment, predicted from an equation shown below:

$$R_N = 0.44 + 9.3t_h + 1.04R_o - 1.77t_h^2 - 0.0012R_o^2 + 0.059R_o \cdot t_h \qquad ......(2.8)$$

in which:

t_h = overlay thickness

Summary Statistics:

R^2 = 0.71

Standard Error = 23.8

F-Value = 51

4. Change in cracking following an overlay:

$$C_N = 0.507 + 0.0687C_o + 0.52C_p - 0.0034I_c^2 - 0.003C_o^2 + 0.0681C_p^2 \qquad ......(2.9)$$

in which:

I_c = index to first cracking

I_c is a function of traffic volume, regional factor, and type of rehabilitation action as defined in Tables 1. If I_c of a rehabilitation action is greater than 16, equation 4 and 2 predict similar change in cracking, which means that such a rehabilitation action is equivalent to new construction with regard to cracking.

Summary Statistics:

R^2 = 0.68

Standard Error = .71

F-Value = 77

2.4.3 Calculation of Transition Probabilities Based on the Regression Equations

The calculation of transition probabilities for a given combination of traffic volume and regional factor was based on the regression equations presented above. Three steps were used to complete the computations (Kulkarni et al. 1980). The three basic steps were repeated for each combination of traffic volume and regional factor to obtain the transition probabilities for that combination.

Step One:

The probability of going from the roughness level of state i to the roughness level of another state j, P_{ij}, was calculated for each i and j, and every rehabilitation action based on equations 1 and 3 for routine maintenance and structural overlay respectively. Figure 2.3 shows the concept of using regression equations to define the transition probability matrix. Assuming a normal distribution for the expected change in roughness, R_N, the probability that R_N will be in a given range can be calculated from the expected value and variance of R_N. The variance is determined from the standard error of the regression equation.

Step Two:

The probability of going from the cracking level of state i to the cracking level of state j, Q_{ij}, was calculated for each i, j, and every rehabilitation action based on Equations 2 and 4 for routine maintenance and structural overlay respectively. Two factors related to cracking are important to the definition of condition state - present amount of cracking, C_o, and change in cracking in previous year, C_p. There are a total of eight combinations of C_o and C_p. The probability, Q_{ij}, of going from i^{th} combination of C_o and C_p to j^{th} combination of C_o and C_p in one year(for all i and j) was recalculated. Based on the same principle of Step One, assuming normal distribution for change in percent cracking C_N, the expected value and variance of C_N were computed.

Step Three:

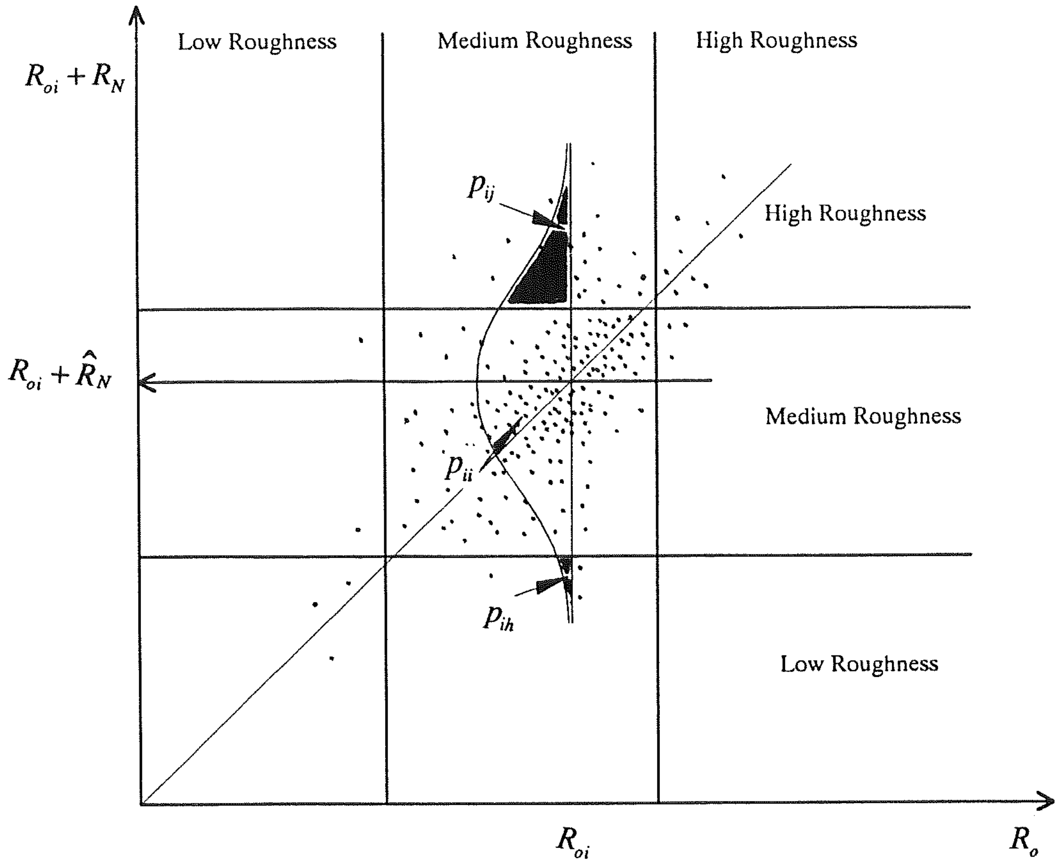
It was assumed that the probabilities of changes in roughness were independent of the probabilities of changes in amount of cracking. Therefore, the one-step transition probabilities, $p_{ij}(a_k)$, can be obtained by multiplying the corresponding probabilities P_{ij} and Q_{ij} as the following:

$$P_{ij}(a_k) = P_{ij} * Q_{ij} \quad \text{for all actions } a_k \qquad ......(2.10)$$

2.5 THE OPTIMIZATION ALGORITHM FOR NOS

The goal of NOS is to formulate cost-effective pavement preservation policies and establish budget levels. The NOS algorithm determines the minimum cost preservation program which maintains the highway network to the specific condition standards for each period (i.e. one year) over the planning horizon. There are 15 road categories, 120 condition states, and 17 rehabilitation actions. For each road category, there are 120^{17} possible alternative rehabilitation policies. Therefore, it is not realistic to compute all the alternatives and compare their cost-effectiveness even in a fast mainframe computer.

As a result, the model is structured as a linear programming problem solved with the Simplex method. The transition process of pavement condition state conforms to the finite-state Markov chain process (Hillier et al., 1974, 1990). The concept of applying Markov chain properties and linear programming technique to maintain manufacturing equipment was explored in the 1960's. The basic model setup of this linear programming formulation coupled with Markov process was described in the books by



p_{ih} = Probability that a pavement in roughness level i will transition to roughness level h in one year;

p_{ii} = Probability that a pavement in roughness level i will stay in roughness level i in one year;

p_{ij} = Probability that a pavement in roughness level i will transition to roughness level j in one year;

R_o = Existing roughness level;

R_N = Change of roughness from R_o;

$\hat{R}_N$ = Standard Deviation of the Normal Distribution.

FIG. 2.3. The Concept of Using Regression Equations to Define the Transition Probability Matrix

Hillier et al. (1974, 1990). It was extended to solve the pavement investment problem for Arizona (Golabi, et al. 1982, Kulkarni, et al. 1980).

2.5.1 The Assumption of Stationary Policy

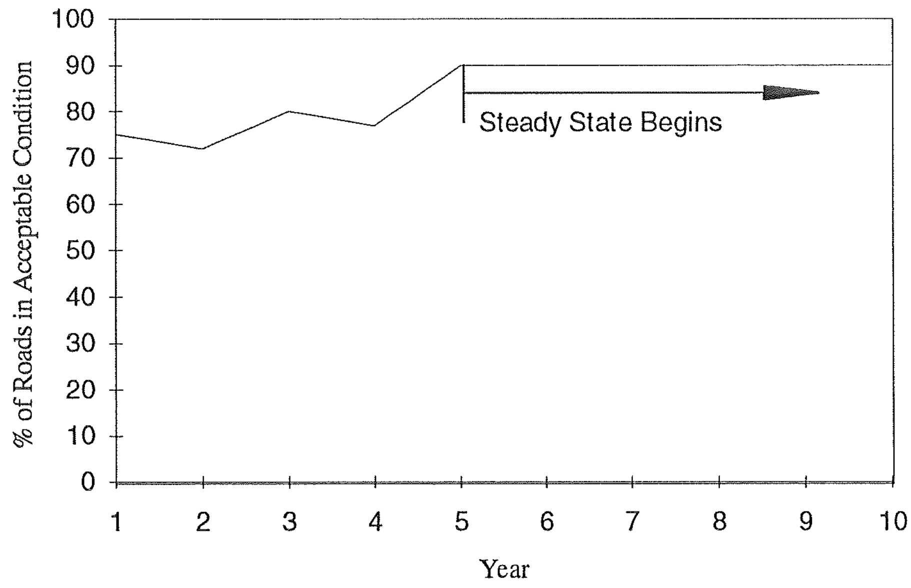
A stationary policy implies the selection of rehabilitation actions will be a function of the pavement condition state and will not be affected by the initial pavement condition states and time. The independence of the stationary policy on the initial pavement condition is due to the fact that under this policy, the condition of the pavements in the network will reach a steady state condition. For example, it is assumed that for the next year, the model selects an ACFC for all pavements with high roughness and low amount of cracking. A stationary policy means that any number of years from now, the pavements in the same condition state will receive the same treatment. Therefore, stationary policy means a uniform policy over a long period of time, assuming that the effects of inflation are uniform for all rehabilitation actions.

If a stationary policy is successfully implemented, the network will achieve steady state condition after some length of time. A steady state condition means that the proportion of roads in the network in each condition state will remain constant over time. Therefore, the yearly preservation budget can remain constant. In practice, however, planning efforts require that a fixed time frame be specified so that steady state is achieved within that time. Therefore, a short-term policy relevant to the initial conditions is sought in addition to the stationary or long-term policy. The time frame during which the short-term policy would be applicable is called the transition period. Depending on the initial pavement conditions, the short-term rehabilitation policies during the transition period can be more expensive than the long-term policy after the network reaches steady state condition. Figure 2.4 shows an example of the expected performance and cost under optimum policies for the highway network under long-term and short-term strategies.

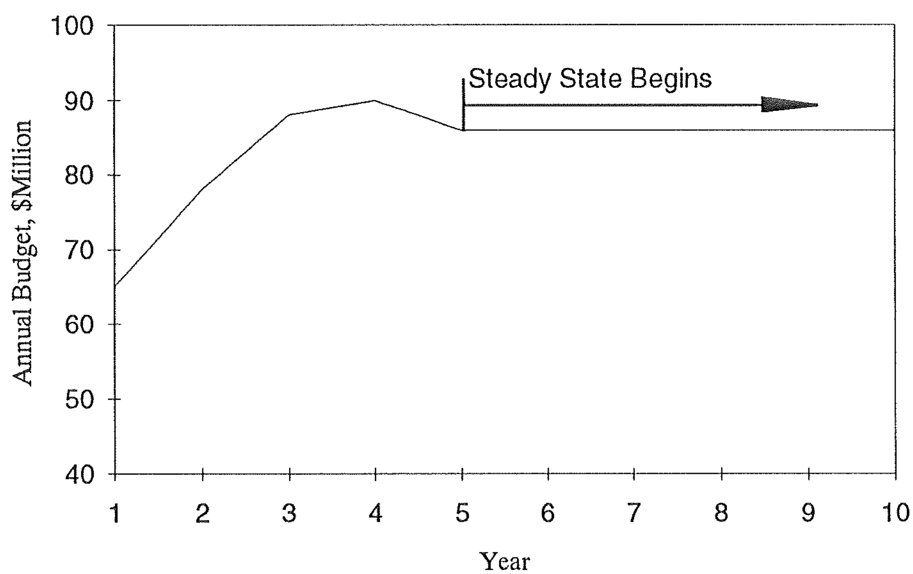
Uniform expenditures may not be the most cost-effective during the transition years after the initiation of the NOS. During the beginning periods of implementing NOS, it may be necessary to increase the maintenance and preservation portion of the budget above a uniform expenditure level to guide the network into a stationary state as indicated in the example (b) of Figure 2.4. Therefore, the steady state policy should be incorporated into the short-term model of NOS.

2.5.2 Model Setup

The model determines the optimum long-term (stationary) rehabilitation policy and the optimum short-term rehabilitation policy (prior to reach steady state) for pavements in each road category. The policies are optimum as they satisfy the prescribed performance standards with minimum cost.



(a). Projected Condition of the Network



(b). Projected Annual Preservation Budget

FIG. 2.4. Expected Network Performance and Annual Budget Under Optimum Policy (Kulkarni, et al. 1980)

The specific form of a rehabilitation policy is in terms of the proportion of roads of a given category in a condition state i to which a specified rehabilitation action k is applied at the l time period. The proportion can be interpreted as the probability that a given pavement would be in state i at time l and action k is taken.

Let $w_{i,k}^{l}$ denote the proportion of roads of a given road category which are in condition state i at the beginning of l^{th} time period of horizon T, and to which k^{th} preservation action is applied. $w_{i,k}^{l}$ is time dependent and reflects the behavior of the system in response to selected rehabilitation strategies. $w_{i,k}$ reflects the steady state condition of the system under a fixed level of funding for rehabilitation and is therefore time independent. The $w_{i,k}^{l}$ and $w_{i,k}$ are the two key variables in the process of setting up the short-term and long-term (steady state) highway preservation policies. Based on the transition matrices and other constraints, $w_{i,k}^{l}$ and $w_{i,k}$ can be determined through the linear programming process. Two stages related to long-term and short-term policies respectively are needed to complete the optimization process. The core of the optimization model lies in the following two transition equations for the two stages optimization respectively:

The Steady State Problem: $$\sum_{k} w_{i,k} = \sum_{i,k} w_{i,k} \cdot p_{ij}(a_k) \qquad ......(2.11)$$

The Multi-Period Problem: $$\sum_{k} w_{j,k}^{l} = \sum_{i,k} w_{i,k}^{l-1} \cdot p_{ij}(a_k), \text{ for } 1 < l \leq T \qquad ......(2.12)$$

The complete model description is as follows:

First Stage: The Steady State (Long-Term) Problem

The Objective:

$$\text{Minimize} \sum_{i,k} w_{i,k} \cdot c(i,k) \qquad ......(2.13)$$

Subject to:

$$\sum_{k} w_{i,k} = \sum_{i,k} w_{i,k} \cdot p_{ij}(a_k) \qquad ......(2.14)$$

$$\sum_{i,k} w_{i,k} = 1 \qquad ......(2.15)$$

$$\sum_{j,k} w_{j,k} \leq \gamma_i, \text{ for } i \in I, j \in j_1(i) \qquad ......(2.16)$$

$$\sum_{j,k} w_{j,k} \geq \varepsilon_i \text{, for } i \in J, j \in j_2(i) \qquad \text{......(2.17)}$$

in which:

c(i,k) = unit average cost of applying k^{th} rehabilitation action to pavements in i^{th} condition state ($ Cost/Square Yard);

$p_{ij}(a_k)$ = probability that a section of pavement in condition state i moves to condition state j in one period if k^{th} rehabilitation is applied;

γ_i = maximum proportion of roads allowed to be in the set of undesirable states denoted by $j_1(i)$;

I = number of specifications of undesirable states;

ε_i = minimum proportion of roads required to be in the set of desirable states denoted by $j_2(i)$;

J = number of specifications of desirable states.

Second Stage: The Multi-Period (Short-Term) Problem

The Objective:

$$\text{Minimize } \sum_{l=1}^{T-1} \sum_{i,k} w_{i,k}^{l} \cdot d_l \cdot c(i,k) \qquad \text{......(2.18)}$$

Subject to:

$$\sum_{k} w_{j,k}^{l} = \sum_{i,k} w_{i,k}^{l-1} \cdot p_{ij}(a_k) \text{, for } 1 < l \leq T \qquad \text{......(2.19)}$$

$$\sum_{k} w_{i,k}^{1} = q_i \qquad \text{......(2.20)}$$

$$\sum_{k} w_{j,k}^{T} \leq \sum_{k} w_{j,k}^{*} \cdot (1+\alpha) \qquad \text{......(2.21)}$$

$$\sum_{k} w_{j,k}^{T} \geq \sum_{k} w_{j,k}^{*} \cdot (1-\alpha) \qquad \text{......(2.22)}$$

$$\sum_{j,k} w_{j,k}^{l} \leq p_1(l) \cdot \gamma_i \text{, for } i \in I, j \in j_1(i), 2 \leq l \leq T \qquad \text{......(2.23)}$$

$$\sum_{j,k} w_{j,k}^{l} \geq p_2(l) \cdot \varepsilon_i \text{, for } i \in J, j \in j_2(i), 2 \leq l \leq T \qquad \text{......(2.24)}$$

$$\sum_{i,k} w_{i,k}^{T} \cdot c(i,k) \le (1+\beta) \cdot c^{*} \qquad \text{......(2.25)}$$

$$w_{j,k}^{l} \ge 0, \text{ for all j, k ,and } 1 \le l \le T \qquad \text{......(2.26)}$$

in which:

l = l^{th} time period;

d = present worth of one dollar spent during l^{th} time period

q_i = current proportion of roads in i^{th} condition state;

α, β = small proportions (e.g. 0.01);

$p_1(l)$ = a multiplier ≥ 1 to permit a higher than γ_i proportion of roads in undesirable states at the l^{th} time period;

$p_2(l)$ = a multiplier ≤ 1 to permit a higher than ε_i proportion of roads in undesirable states at the l^{th} time period;

$w_{j,k}^{*}, c^{*}$ = the answer from stage one (steady state). The values of $w_{i,k}^{T}$ should be as close as to $w_{j,k}^{*}$ as is practically possible and the cost at the T^{th} time period is within a small percentage of the cost of the optimum steady state solution c^{*}.

The NOS was implemented in an Amdahl mainframe computer in ADOT. The routine of MPSX is used as the linear programming optimizer for NOS. The Flow chart to solve NOS problem is shown in Figure 2.5.

2.5.3 The Output of NOS and Analysis

An example of an edited output summary is shown in Table 2.9, which include the information on control data and optimum budget policy of a five-year horizon. The rehabilitation table and current pavement conditions are omitted due to their lengths. A five-year horizon was used for this short-term NOS run within the road category of interstates of high traffic in desert region.

The short-term optimum rehabilitation policy generally results in a non-uniform distribution of costs in the first few years as shown in Table 2.9. In the example run, a number of actions were assigned to be infeasible for many of the condition states. For example, when no infeasible actions are assigned to the system, the only rehabilitation action selected by the optimizer other than routine maintenance was ACFC by the optimizer. In other words, the system cannot differentiate the cost-effectiveness of alternative rehabilitation actions. This problem results from the insensitivity of the transition probability matrices to the differences in the cost-effectiveness of the rehabilitation actions.

Numerical difficulties in running steady state NOS have been experienced since the implementation of the original NOS. These difficulties might be stemmed from the original transition probability matrices,

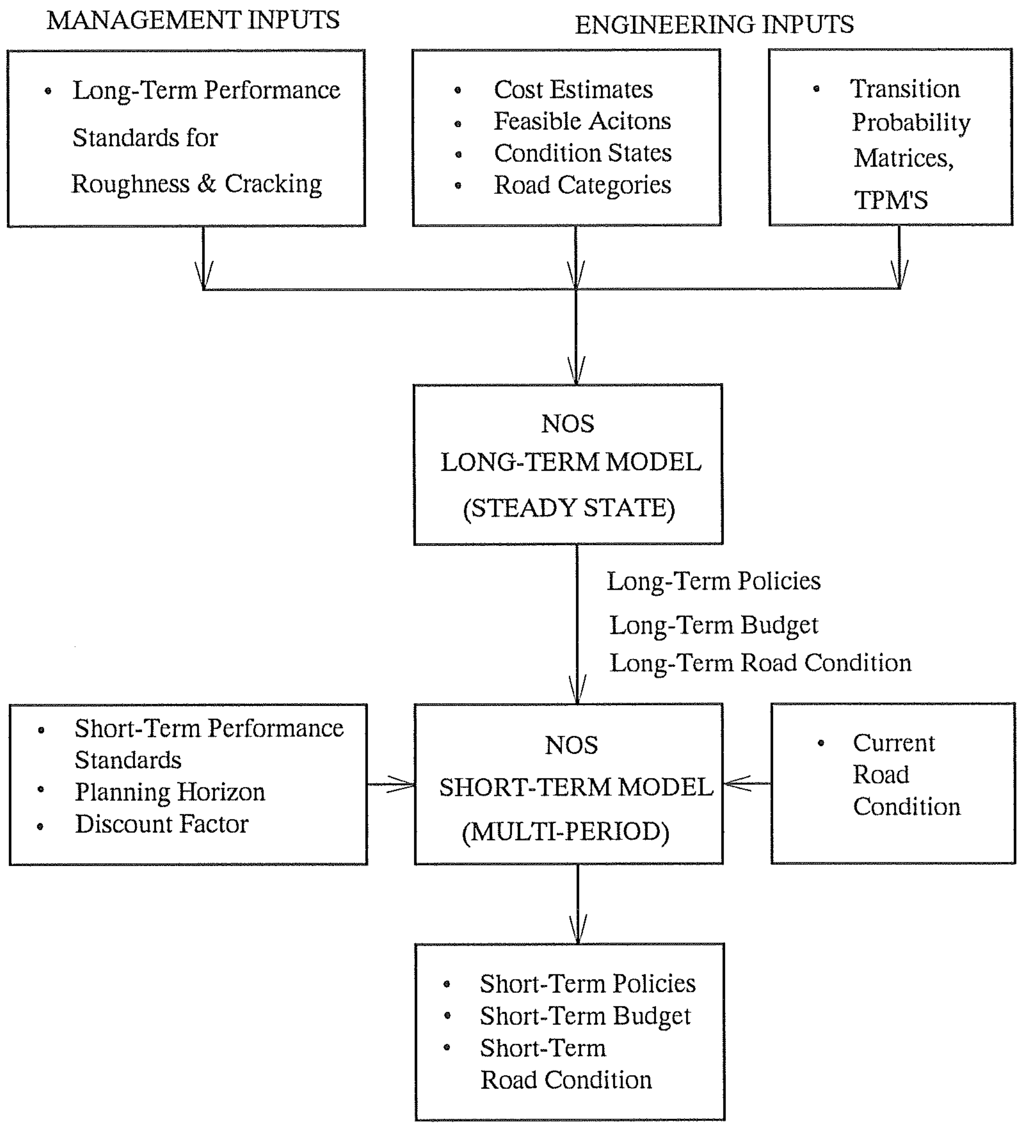


FIG. 2.5. Flow Chart of Solving A NOS Problem

TABLE 2.9. Optimum Budgetary Policy of a 5-Year Multi-Period NOS Run

Problem Information	Road Category: Interstate, High Traffic, Desert Region Total Area in Square Yard: 16,492,000				
Infeasible Action List	Based on Engineering Judgment: Make Heavy Actions Infeasible for Pavements in Good Conditions; Make Light Actions Infeasible for Pavements in Bad Conditions				
Performance Information		Standards		Achieved	
		Roughness (Desirable)	Roughness (Undesirable)	Cracking (Desirable)	Cracking (Undesirable)
Year 1		0.76	0.10	0.73	0.05
Year 2		0.81	0.05	0.77	0.03
Year 3		0.86	0.02	0.81	0.01
Year 4		0.90	0.02	0.86	0.01
Year 5		0.95	0.02	0.90	0.01
Budget Information			Routine Maintenance	Light Rehab.	Heavy Rehab.
Year 1	% of Road		0.97	0.02	0.01
	$ in 1000		799	1944	1479
Year 2	% of Road		0.88	0.11	0.01
	$ in 1000		706	11,022	2098
Year 3	% of Road		0.98	0.01	0.01
	$ in 1000		802	1061	440
Year 4	% of Road		0.86	0.11	0.03
	$ in 1000		686	10,775	5,024
Year 5	% of Road		0.78	0.18	0.04
	$ in 1000		413	4452	8011

which were based on limited data. However, ADOT pavement management group has been successfully using the results of multi-period NOS runs for the pavement preservation program. The last year of the planning horizon was assumed to achieve the pseudo steady state, when the differences among the annual budgets for the last years were so small that the system being optimized by NOS could be considered stabilized. Therefore, the numerical difficulty to run steady state NOS was not a problem for the implementation of NOS.

The basic output of the optimization model does not identify the rehabilitation action that should be applied to a specific pavement section in the state. Although an action list can be generated for each mile of the network and for each period of the planning horizon, it is impractical to implement rehabilitation actions on one-mile segments of pavement.

2.6 CONCLUSION

The output of NOS enables ADOT management to determine:

- What proportion of the pavements in each road category will be expected to be in various condition states at the beginning of each time period,
- What is the most cost-effective rehabilitation action for every mile of pavement in the network at each time period, and
- What are the expected annual costs of pavement rehabilitation and routine maintenance.

These questions can be answered from two perspectives: the long-term-based steady state runs and short-term-based multi-period runs. For more than 10 years, the highway preservation program based on these answers from NOS has been providing the management, the State Transportation Board and the State Legislature information on the needs of the state highway system.

It should be noted that the direct inclusion of user costs, or excess user costs, in the NOS was considered during the initial stages of NOS development. But user costs were indirectly and partially addressed by the inclusion of the factor of ride quality.

Since the implementation of NOS in Arizona, new computer developments and technologies have become available. Subsequently, efforts were made to implement NOS in the microcomputer environment. In the process of porting NOS to a 32-bit microcomputer platform, several problems were discovered. Chapter 3 addresses the problems of NOS in detail and recommends revisions to the structure and methodology used in NOS accordingly.

CHAPTER 3

REVISIONS TO THE NETWORK OPTIMIZATION SYSTEM

3.1 INTRODUCTION

NOS is a very effective financial planning tool for pavement preservation program based on relatively small amount of current pavement information. Only roughness and cracking information on existing pavement is needed to conduct NOS runs. In addition, the capability of conducting long-term pavement financial analysis and providing reliable information are the important driving forces for ADOT to continue relying on this important tool for the preservation program.

However, the mathematical model of NOS is very sophisticated which includes two major operations research techniques, Markov process and linear programming. A mathematical model is intended to be a representation of the real problem in the major areas of concern. Approximations and simplifications are generally required in order for the model to be effective and tractable. In addition, there must be a reasonably good correlation between the performance prediction and what would actually happen in the future. Based on the experience in using and examination of the mainframe based NOS, it was determined that a comprehensive analysis of the current system is needed. Furthermore, the current state of the art and available data bases provide the means to revisit the original developments and subsequent revisions can be made where it is deemed necessary.

Modeling the performance of pavements is an essential activity of any pavement management. Since the heart of the prediction methodology used in NOS is the transition probability matrices, TPM's, they are examined in this chapter. The regression equations were the basis for generating the original transition probability matrices. Due to inadequate data, sample data were used to build the regression equations. It was also assumed that the performance prediction of both interstates and non-interstates could share the same set of TPM's. However, the structural characteristics of interstate and non-interstate highways are different. Traffic volumes in interstate highways are normally substantially higher than traffic volumes in non-interstate highways. Therefore, probabilistic behavior of pavement condition transition for both interstate and non-interstate highways are different. The inclusion of the infeasible actions list as an input option indicates that the model needs human intervention to produce reliable results.

There are four factors used to determine pavement condition. Three of the four factors address structural capabilities of pavement. As in most cases ride quality dominates rehabilitation strategies, this indicates that the number of factors may need to be reduced. As a result, the size of TPM's can be reduced too. In addition, the number of TPM's required by the system are probably excessive. The number of TPM's can be reduced by consolidating the number of actions analyzed.

Furthermore, the existing levels for the boundaries defining condition states are not representative of the levels used by the engineering staff for determining rehabilitation needs or actions. The TPM's were evaluated with respect to long term behavior and new TPM's were developed based on the pavement management data base.

Under the current system, poor pavements can transition to good condition under routine maintenance. This is attributed to the original assumption that the transition probabilities conform to normal distribution. As shown in Figure 2.3, pavement transition probability p_{ih} from medium roughness level to low roughness level could be calculated under routine maintenance. This behavior does not occur in the field during a long observation period, so *accessibility* rules were introduced to prohibit some of the transitions from occurring in the model.

3.2 PAVEMENT PERFORMANCE MODELING

The concepts of pavement performance include functional performance, structural performance, and safety. The structural performance of a pavement relates to its physical condition, i.e., occurrence of cracking, rutting, or other conditions which would adversely affect the load-carrying capacity of the pavement structure or would require rehabilitation or maintenance. The functional performance of a pavement concerns how well the pavement serves the user. Riding comfort or ride quality is the dominant characteristic (AASHTO, 1986). In order to quantify riding comfort, the *serviceability-performance* concept was developed by the ASSHO Road Test staff in 1957 (AASHO Road Test, 1962). The area of safety performance is a separate subject which is not covered in this study.

The serviceability of a pavement is expressed in the terms of the *present serviceability index*, PSI, the scale of which ranges from 0 through 5, with a value of 5 representing the highest index of serviceability. The PSI is obtained from measurements of roughness and distress, e.g., cracking, patching and rut depth, at a particular time during the service life of the pavement. However, roughness is the dominant factor in estimating the PSI of a pavement. Therefore, a reliable method for measuring roughness is important in monitoring the performance history of pavements.

Because of the relative small contribution to PSI made by physical distress, and the difficulty in obtaining reliable information, many agencies rely only on roughness to estimate ride quality (AASHTO, 1986). *Serviceability Index*, SI, is used by ADOT to measure the serviceability of pavements. It is a function of Maysmeter numbers as shown by equations (2.1) and (2.2).

Modeling of pavement performance is essential to pavement management regardless of whether it is at the project level or network level. The performance equation used in the *AASHTO Guide for Design of Pavement Structures* (AASHTO, 1986) is a classical example of pavement performance prediction:

$$\log_{10} W_{18} = Z_R \cdot S_o + 9.36 \cdot \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \cdot \log_{10}(M_R) - 8.07$$

......(3.1)

Where:

W_{18} = predicted future traffic (18,000 lb. single axle load) for the performance period,

Z_R = z statistic for a specified level of reliability,

S_o = combined standard error of the traffic prediction and performance prediction,

SN = structural number,

ΔPSI = difference between the initial design serviceability index, p_o, and the design terminal serviceability index, p_t, and

M_R = resilient modulus (psi).

3.2.1 Methods used in Pavement Behavior Modeling

As defined by Lytton (1987), there are several types pavement behavior models. Behavior, in its broadest sense, is predicted by deterministic and probabilistic models. The deterministic models include those for predicting primary response, structural, functional, and damage behavior of pavements. The probabilistic models include survivor curves, Markov and semi-Markov transition processes. Table 3.1 shows the types of performance models which may be used at various levels of pavement management.

Lytton further points out the following significant items in pavement behavior and modeling:

- principles underlying each type of model,
- selection of the model mathematical form,
- role of statistics and mechanics in developing an efficient model,
- data needed for a specific model,
- modification of each model to represent the effects of maintenance, and
- limitations and uses of specific models.

Pavement behavior models can be developed by using the techniques such as:

- regression analysis (least squares),

TABLE 3.1. Types of Performance Models used in Pavement Management (Based on Lytton et al 1987)

PERFORMANCE MODELS		LEVELS OF PAVEMENT MANAGEMENT			
		National Network	State Network	District Network	Project Level
DETERMINISTIC	Primary Response • Deflection • Stress • Strain • etc.				*
	Structural • Distress • Pavement Condition		*	*	*
	Functional • PSI • Safety		*	*	*
	Damage • Load Equivalent	*	*	*	*
PROBABILISTIC	Survivor Curves	*	*	*	
	Markovian	*	*	*	
	Semi-Markovian	*	*	*	

- transition probability matrix, TPM, based on Markovain process, and
- Bayesian methodology.

Regression analysis is a statistical tool used to relate two or more variables. The technique of least squares is used to minimize the differences between the actual data points and their corresponding points on the fitted line, or curve if it is a non-linear regression. This technique of linear regression, combined with statistical tools, was used in the development of behavior equations for ADOT PMS, specifically, the Network Optimization System (Way et al. 1980).

Bayesian methodology allows both subjectively and objectively obtained data to be combined and predictive (regression) equation be developed. This approach can also be used to produce regression equations exclusively from subjective information. For example, Smith et al. (FHWA 1991) obtained opinions from engineers in several state highway agencies, SHA's, in order to develop predictive equations. The principal model was to relate pavement distress, e.g., fatigue life in year, or y, to various design variables, x's , such as asphalt consistency (x_1, penetration), asphalt content (x_2, percent asphalt by weight of mix), asphalt concrete proportion (x_3, percent thickness of the pavement materials above the subgrade) and base course density (x_4). By using both subjective data (opinions), and objective data (based on mechanistic models), a linear equation of the following format was developed:

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_4 \qquad \text{......(3.2)}$$

Where

b_0, b_1, b_2, b_3, b_4 are parameters and are assumed to be random variables with associated probability distributions (value of mean and standard deviation).

Karan et al (1976) conducted early modeling research by using Markov process for pavement performance prediction. Rauhut et al. (1987) present analysis on prediction models for the SHRP long-term pavement performance program. Jackson et al. (1987) describe the methodologies used by WSDOT in establishing project specific performance curves. Methods on performance prediction and risk modeling is given by Cook et al. (1987)

3.2.2 The Application of the Markov Process to PMS

Markovian prediction model is the basis for many optimization programming based PMS's due to its flexibility to fit mathematical models. It has been successfully applied in a number of state highway agencies and other institutions in the areas such as queuing theory, inventory and probabilistic dynamic programming (Hillier, et al. 1990).

The transition process of the pavement condition states in NOS is assumed to conform to the finite-state Markov chain process. The current pavement condition is only dependent on its preceding condition. Furthermore, future pavement condition is dependent only on the preceding pavement condition. For example, as shown in Table 3.2, assume under routine maintenance, the total number of pavement condition for high traffic road category of interstate at desert region is 9 states with state 1 of the best condition and state 9 the worst. Given a pavement whose condition state is 2 in current year. The next year there is 0.72 probability that the pavement will stay in state 2, 0.15, 0.08, 0.05 probabilities in states 3, 5, 6 respectively. It should be noted that the values for most of the cells are zero. Also the assumption based on the Markovain property implies that the pavement condition at next year is independent of how the pavement attained the current condition state.

3.2.3 The Modeling of Pavement Long-Term Probabilistic Behavior based on the Chapman-Kolmogorov Equations

The matrix of n-step transition probabilities can be obtained by multiplying matrices of one-step transition probabilities based on the Chapman-Komolgorov equations (Hillier, et al. 1990) as follows:

$$\mathbf{P}^{(n)} = \mathbf{P}\cdot\mathbf{P}\cdots\mathbf{P} = \mathbf{P}^{n} \qquad \text{......(3.3)}$$

Therefore, the transition probabilities of pavement condition for a period of n years can be obtained based on the existing one-step transition probabilities of pavement condition. This allows a probabilistic prediction of pavement behavior over the life of structure. Similar concepts are presented by Karan et al. (1976), and equation 2.33 of Feighan et al (1987). The Chapman-Kolmogorov equations can be used to predict long-term pavement probabilistic behavior. Validation of TPM's can also be conducted based on the examination of the probabilistic behavior. The analysis of long-term pavement performance in the following sections uses the Chapman-Kolmogorov Equations.

Traditionally, a performance model is illustrated by a performance curve as shown in Figure 3.1. The deterioration of a pavement starts from the best condition state when it is new until the serviceability of the pavement is not acceptable and an overlay is applied. Pavement condition is improved with a rehabilitation action, then deterioration resumes. As define by Haas et al. (1978), a true performance prediction model is one that can calculate the expected serviceability-age (or traffic) relationship over the entire design period.

The pavement behavior modeling based on the Chapman-Kolmogorov equations provides an alternative to demonstrate the pavement long-term probabilistic behavior as shown in equation 3.3. Furthermore, pavement behavior can be determined for the entire design period even if rehabilitation action(s) are applied during this period of time as determined as the following. Assume that the design period for the pavement is from 0 to N. At the period of v, a rehabilitation action is applied. The pavement probabilistic behavior equation is shown as the following:

TABLE 3.2. Transition Probability Matrix under Routine Maintenance, High Traffic Road Category of Interstates at Desert Region

TO STATE	1	2	3	4	5	6	7	8	9
FROM STATE									
1	0.85	0.06	0.00	0.08	0.01	0.00	0.00	0.00	0.00
2	0.00	0.72	0.15	0.00	0.08	0.05	0.00	0.00	0.00
3	0.00	0.00	0.74	0.00	0.00	0.26	0.00	0.00	0.00
4	0.00	0.00	0.00	0.87	0.06	0.00	0.07	0.00	0.00
5	0.00	0.00	0.00	0.00	0.64	0.16	0.00	0.04	0.16
6	0.00	0.00	0.00	0.00	0.00	0.87	0.00	0.00	0.13
7	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.06	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.05
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

$$p_{ij}^{(n)} = \begin{cases} \sum_{k=0}^{M} p_{ik}^{(m)} \cdot p_{kj}^{(n-m)}, & \text{when} \, n < v; \\ \sum_{k=0}^{M} p_{ik}^{(v)} \cdot p_{ik}^{(1)} \cdot p_{kj}^{(n-v-1)}, & \text{when } n \geq v; \end{cases}$$

for all i, j, l, n, and $0 \leq v \leq N$, $0 \leq n \leq N$

......(3.4)

Where:

$p_{ij}^{(n)}$: n-step transition probability from condition state i to j. When $n=N$, it is the transition probability for the entire design period;

m : any intermediate period;

$M+1$: the total number of pavement condition states;

N : the design period;

v : the period when the rehabilitation is applied;

$p_{ik}^{(v)}$: v-step transition probability from condition state i to k under routine maintenance. A rehabilitation action is applied after the v steps or periods;

$p_{kl}^{(1)}$: one-step transition probability from condition k to l at period v. It is the probability concerning the effectiveness of the rehabilitation action to improve the serviceability of the pavement;

$p_{lj}^{(n-v-1)}$: (n-v-1) step transition probability from condition l to j under routine maintenance. It is the transition probability after the rehabilitation.

It should be noted that equation 3.3 can be easily expanded to analyze pavement probabilistic behavior where more than one rehabilitation actions are applied. Based on the same deduction in section 2.3.4, the following pavement probabilistic behavior equation can be established:

$$\mathbf{P}^{(\mathbf{n})} = \begin{cases} \mathbf{P}_{\mathbf{a}}^{(\mathbf{n})}, & n < v \\ \mathbf{P}_{\mathbf{b}}^{(v)} \cdot \mathbf{P}_{\mathbf{c}}^{(1)} \cdot \mathbf{P}_{\mathbf{d}}^{(\mathbf{n}-v-1)}, & n \geq v \end{cases} \qquad \text{......(3.5)}$$

Where:

$\mathbf{P}^{(\mathbf{n})}$: n-step TPM;

$\mathbf{P}_{\mathbf{a}}^{(\mathbf{n})}$: n-step TPM before the rehabilitation when n<v;

$\mathbf{P}_{\mathbf{b}}^{(v)}$: v-step TPM when the rehabilitation is applied;

$\mathbf{P}_{\mathbf{c}}^{(1)}$: the one-step TPM based on the effectiveness of the rehabilitation at the period of v;

$\mathbf{P}_{\mathbf{d}}^{(\mathbf{n-v-1})}$: (n-v-1)-step TPM after the rehabilitation.

As shown in the equations 3.3 and 3.4, three TPM's are needed to conduct the analysis of long-term probabilistic behavior for the entire design period during which one rehabilitation is applied. The data generated based on equation 3.4 can be used to plot pavement probabilistic behavior curves, or P.B.C.. Each condition state has its own set of P.B.C.'s over time. As the best condition state with the lowest roughness and cracking levels is a critical behavior standard set by ADOT, it was used in Figure 3.2 for demonstration. Figure 3.2 illustrates typical long-term probabilistic behavior curves, P.B.C.'s, of design period N for interstate pavement. It is interesting to see that the curve pattern for the traditional performance curve is convex whereas the curve pattern for the P.B.C. is concave.

Karan et al. (1976) present a Markov model for predicting pavement performance:

$$\mathbf{V(n)} = \mathbf{V(0)} \cdot \mathbf{M^n} \qquad \text{......(3.6)}$$

Where:

$\mathbf{V(n)}$: Predicted condition state matrix at year n;

$\mathbf{V(0)}$: Initial condition state matrix at year 0;

$\mathbf{M}$: One-step TPM.

Another study conducted by Feighan et al. (1987) revealed similar relationship between initial condition state and the predicted condition state. Both studies by Karan and Feighan use the technique of matrix multiplication to derive n-step TPM's. However, the prediction presentation and analysis are not detailed in either reference.

The relationship displayed by equation 3.5 can be obtained from the NOS mulit-period transition equation 3.12 as presented in section 3.6.2:

$$\sum_{k} w_{j,k}^{l} = \sum_{i,k} w_{i,k}^{l-1} \cdot p_{ij}(a_k), \text{ for } 1 < l \leq T$$

Assume that no rehabilitation action is applied after period 0. Therefore, k is equal to 1 for routine maintenance for the analysis period T. Then we have:

$$w_{j,1}^{l} = \sum_{i} w_{i,1}^{l-1} \cdot p_{ij}(1) \qquad \text{......(3.7)}$$

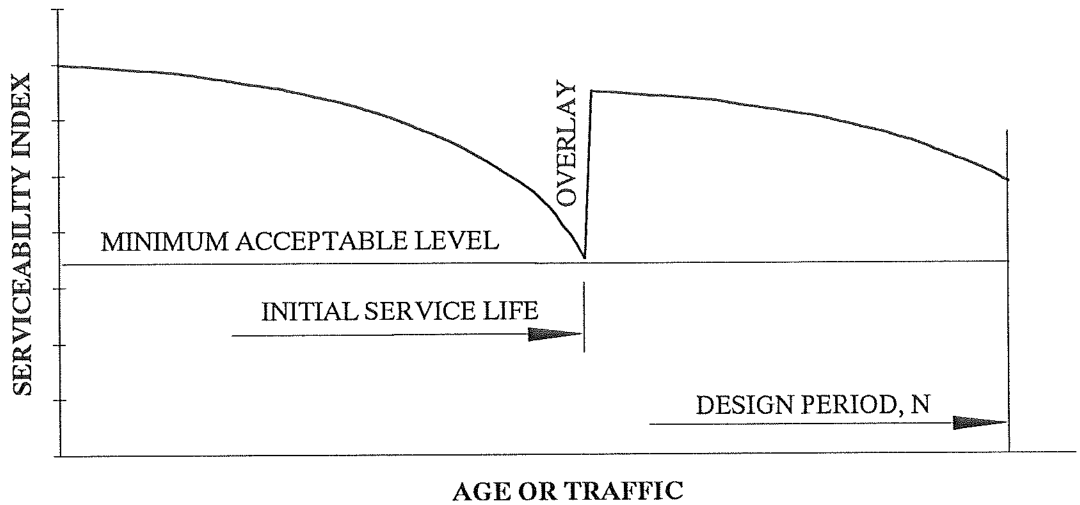


FIG. 3.1. Illustration of Pavement Performance and Prediction

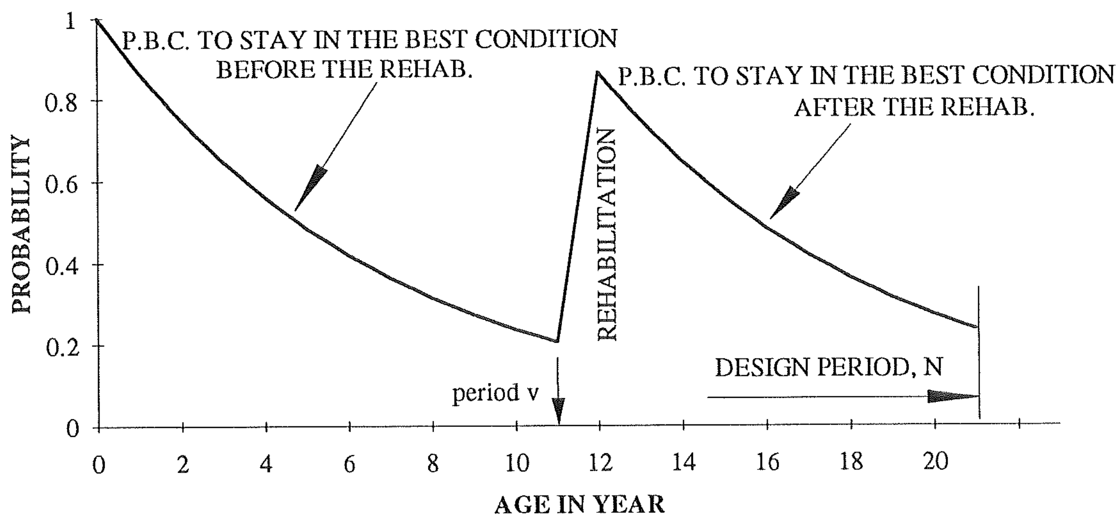


FIG. 3.2. Typical Pavement Probabilistic Behavior Curves for the Design Period

Where:

$p_{ij}(1)$: one-step transition probability from condition state i to j under routine maintenance.

Convert equation 3.6 to vector form:

$$\mathbf{w}^{l} = \mathbf{w}^{l-1} \cdot \mathbf{p}_{ij}(1) \qquad \text{......(3.8)}$$

Equations 3.6 and 3.7 are recursive. Therefore:

$$\mathbf{w}^{l} = \mathbf{w}^{0} \cdot \mathbf{p}_{ij}^{l}(1) \quad 1 < l \le T \qquad \text{......(3.9)}$$

Where:

$\mathbf{w}^{0}$: vector of initial pavement condition states

Section 3.6.2 presents examples of pavement condition prediction. It is cautioned that the prediction model based on Markov process in NOS is an aggregate prediction system based on statistical assumptions. Therefore, the model is not applicable for site specific prediction.

3.3 REVISIONS TO THE STRUCTURE OF THE NETWORK OPTIMIZATION SYSTEM

3.3.1 Reducing the Size of Transition Probability Matrices, TPM's

The current matrix structure of the TPM's in NOS consists of 15 road categories, 17 rehabilitation actions, including routine maintenance, seal coat and 15 rehabilitation actions, and 120 condition states. Total number of matrices is 15 x 17 = 255 based on the combination of the number of road categories, 15, and the action number, 17. Each matrix has 120 "from states" and 120 "to states". The number and sizes of the TPM's in the NOS indicate that they are capable of including vast amount of information. However, the factors and methodologies used to define pavement conditions and transitions should be effective in providing sufficient data to the optimization process, not just be inclusive of any information which appear to be related to the pavement design and management process.

Based on more than 10 years' experience in using NOS in Arizona, the dominant factor influencing highway preservation budget is pavement roughness. This experience is augmented by the statements made in AASHTO Guide for Design of Pavement Structures (AASHTO 1986) that *roughness is the dominant factor in estimating PSI of a pavement, and because roughness is such an important consideration for the design of pavements, the change in roughness will control the life cycle of pavements*. As shown in Figures 3.3 to 3.6, in the presence of the performance standards set by ADOT management, the roughness and cracking levels of the interstate network are presented from 1973 to 1991. It is evident that actual network cracking behavior has consistently met the standards every year (Figures 3.3 and 3.4). However, the annual roughness levels of the network have been struggling to keep up to the standards (Figures 3.5, 3.6). In most of the years, the standards were not met at all for the high traffic road category of the interstates network. The patterns for non-interstates network are very similar to interstates.

Of the four factors used to define the condition state of the pavement, three are related to pavement distress: amount of crack, crack change and index to first crack. Amount of crack is an important indicator of the structural soundness of a pavement. In addition, it is also used as one of the two performance standards. Therefore, the factor of amount of crack must stay in the system.

The original definition of index to first crack was the number of years for the first crack to appear in the pavement after a rehabilitation. However, the concept of using the factor of index to first crack was to differentiate the cost-effectiveness of different rehabilitation actions, as it was assumed to be instrumental in selecting the best strategy for specific pavements. In the actual NOS model structure, the index as defined above is not used, rather five levels of classification of the 17 rehabilitation actions based on this index are used to differentiate cost-effectiveness. Therefore, the factor of index to first crack is only indicative as far as its original definition is concerned.

Therefore, only the factor of crack change, C_p, is a candidate for elimination from the system. When the structure of the condition states was set up in the early 80's, there was little information regarding the crack change in the pavement management data base. During the period of the development of the system it was assumed that crack change would play an important role in predicting pavement structural deterioration rate. However, examining the pavement performance data base shows that crack change over 5 percent is a rare event as shown in Table 3.3. Only 4.2% of interstates and 6.5% of non-interstates sections had a crack change, from one year to the next, of more than 5%. In addition, the occurrences of crack changes over 15% occurred in less than one percent of the records.

The traditional assumption regarding pavement structural deterioration is that the rate of deterioration accelerates upon the initial cracking occurrence. However, Table 3.4 demonstrates that more than five percent crack change in one year does not indicate that there will be a high level of crack in the following year. This is in conflict with the concept that the rate of distress development increases as the pavement deteriorates. The failure of the data to demonstrate an increasing rate of deterioration could be attributed to the 5% level of crack change used in the analysis. However, the deviations of visual examination of percent cracking can be as high as 5% at the same location either by different field crew or at different times within one year. This deviation can be even higher when the pavement is highly cracked. For example, when a pavement is 20% cracked, it is very possible that the visualized percent crack range is between 15% to 25%. Therefore, the analysis based on the 5% level of crack is reasonable.

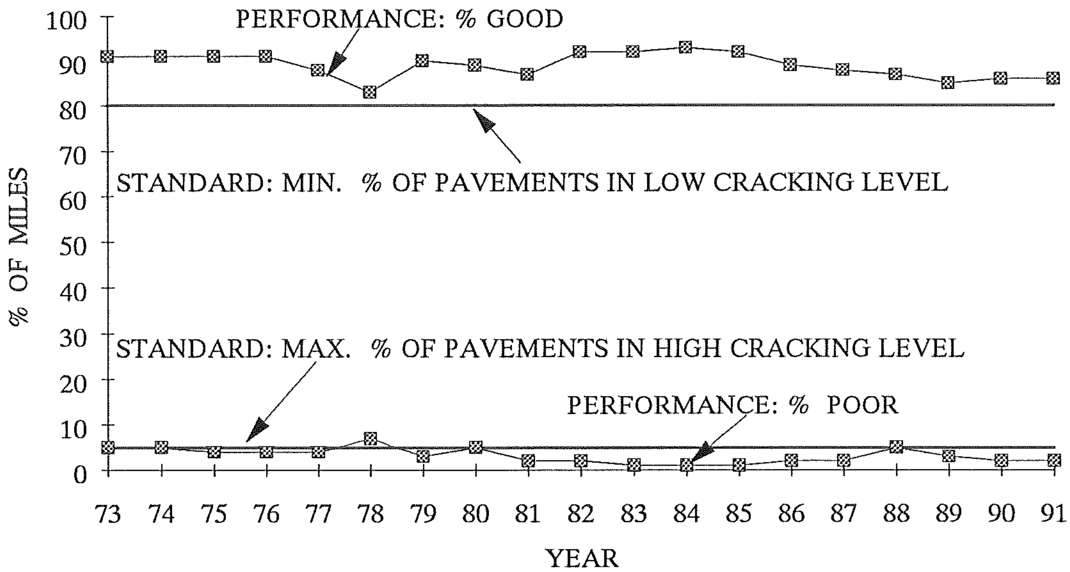


FIG. 3.3. Pavement Cracking Levels of Medium Traffic Category of Interstate Network , AC Pavement (532 miles), ADT 2000 - 10,000

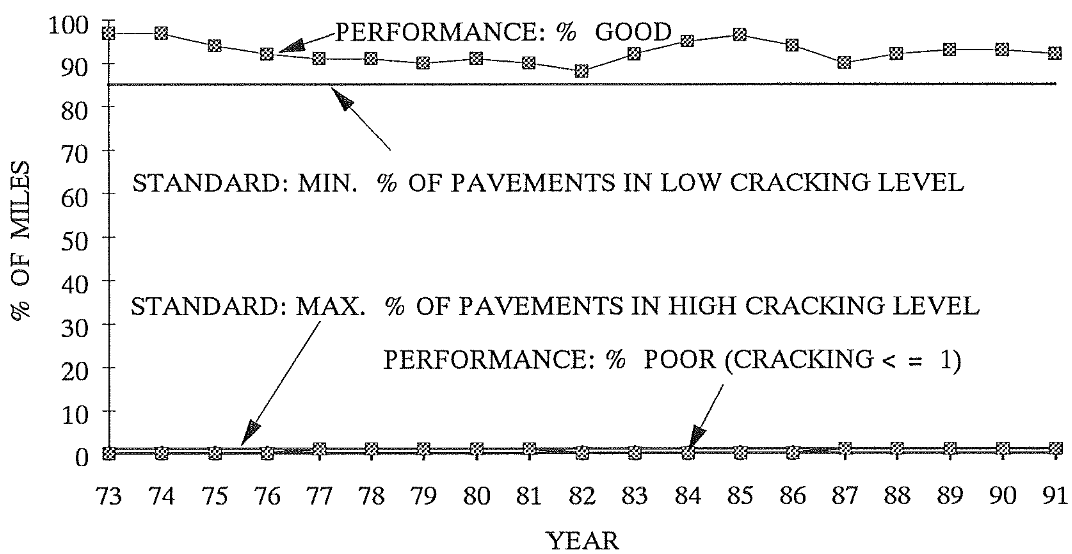


FIG. 3.4. Pavement Cracking Levels of High Traffic Category of Interstate Network , AC Pavement (1655 miles), ADT 10,000 +

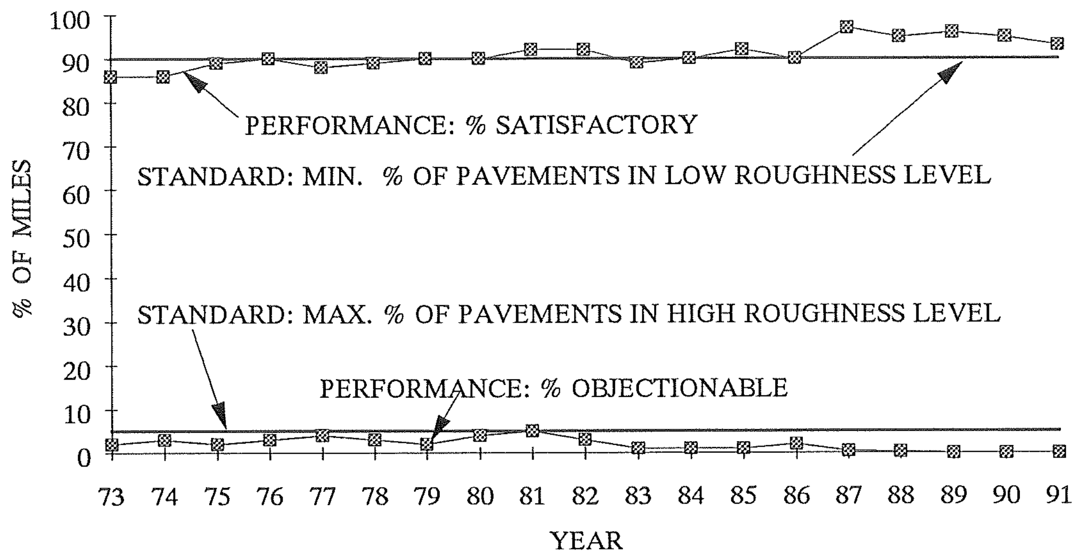


FIG. 3.5. Pavement Roughness Levels of Medium Traffic Category of Interstate Network , AC Pavement (532 miles), ADT 2000 - 10,000

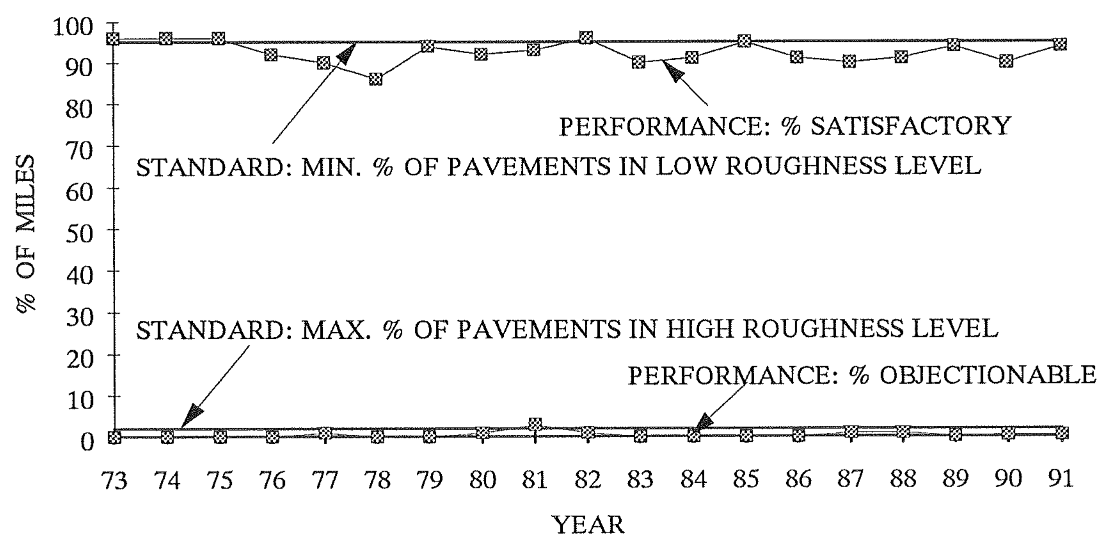


FIG. 3.6. Pavement Roughness Levels of High Traffic Category of Interstate Network , AC Pavement (1660 miles), ADT > 10,000

A further evidence is illustrated in Figure 3.7. The data of percent crack for the Interstates were averaged on a yearly basis for 15 years. It shows that there was an average of four and half years between the rehabilitation and the occurrence of the first crack for the network. When the percent crack increased over the next 11 years as shown in Figure 3.7, the relationship of crack change over time is approximately linear. The rapid pavement structural deterioration after the development of first crack was not observed in this figure.

Based on the discussion, it is evident that crack change, as defined in the existing system, is not an important indicator of future pavement condition in Arizona. Eliminating crack change reduces the number of pavement condition states from 120 to 45. The new structure of condition states is shown in Table 3.5.

3.3.2 Reducing the Number of Rehabilitation Actions

There are a total of 17 rehabilitation actions in the original NOS. The initial concept of using this number of actions was to provide guidance for the pavement design process to select the *best* overlay design strategy. Based on the effectiveness of the action in the year of application, there are three categories of actions, routine maintenance, light treatments, and heavy treatments. Light treatments have an index to first crack of 2 but the initial affect of the treatments in this category varies depending on the type of action, i.e., a seal coat does not improve roughness but ACFC 's and ACSC's improve roughness. Heavy treatments, with index to first crack of 3 to 5, have a high probability, approaching 1.0, of improving the pavement to the best condition state. In the NOS all actions with a particular index to first crack use the exact same transition probabilities under routine maintenance. Therefore, the NOS only models the behavior of five action groups under routine maintenance, one for each index to first crack. This restricts the NOS to selecting the least cost actions for the heavy treatment categories. Due to the difference in the initial condition within the light treatment category, the NOS can distinguish between the effectiveness of the seal coats and the other light treatments.

Therefore, the NOS can only optimize on six actions, not 17. Experience with running the NOS supports this conclusion. The infeasible actions input to the NOS was used to restrict the systems use of actions that were deemed inappropriate for certain condition states. Therefore, since the model can only select from six actions, the structure of the model can be simplified by eliminating 11 actions, without compromising the effectiveness of the model. The new rehabilitation actions are shown in Table 3.6. The first action is routine maintenance. It is the do-nothing action when no other action is selected. Action 2 is re-surfacing type applications including seal coat, ACFC and ACSC. Actions 3 to 5 are structural overlays in the order of increasing costs. It should be noted that even though seal coat, ACFC and ACSC are grouped into one rehabilitation action group, the application of seal coat has its own unique transition pattern. The

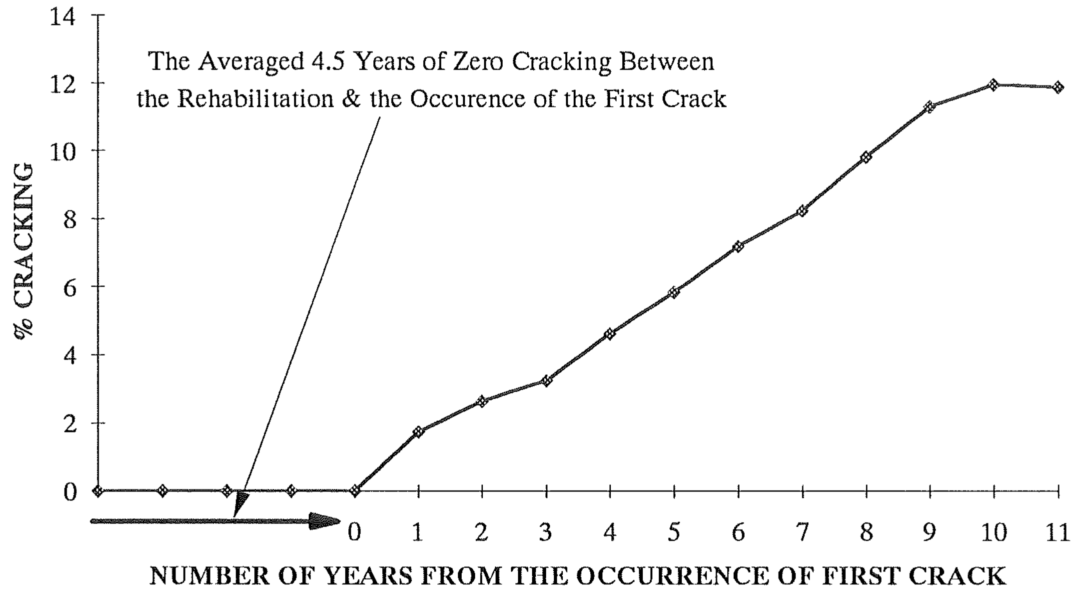


FIG. 3.7. The Average Percent Cracking Over Time After the Rehabilitation for Interstate Highways

TABLE 3.3. Percent of Records in Crack Change

Crack Change	% of Total Record-Year (Interstate)	% of Total Record-Year (Non-Interstate)
0 to 5 Percent	95.90%	93.50 %
6 to 15 Percent	3.80%	5.90 %
Over 15 percent	0.30 %	0.6 0%

TABLE 3.4. Percentage of Records in Consecutively Multi-Year Crack Change over 5%

Multi-Year Crack Change Over 5%	% of Total Record-Year (Interstate)	% of Total Record-Year (Non-Interstate)
Consecutively Two-Year	0.40%	0.57%
Consecutively Three-Year	0.03%	0.06%
Consecutively Four-Year	0.00%	0.00%

TABLE 3.5. The New Condition State Numbering System

R_o	C_o	INDEX TO FIRST CRACK, I_c				
		1	2	3	4	5
1	1	1	10	19	28	37
1	2	2	11	20	29	38
1	3	3	12	21	30	39
2	1	4	13	22	31	40
2	2	5	14	23	32	41
2	3	6	15	24	33	42
3	1	7	16	25	34	43
3	2	8	17	26	35	44
3	3	9	18	27	36	45

TABLE 3.6. New Action Groups of the Rehabilitation Actions

ACTION GROUP	ACTIONS	AVE. COST($/SY) INTERSTATE	AVE. COST($/SY) NON-INTERSTATE
1	ROUTINE MAIN.	0.05	0.05
2	SEAL COAT, ACFC, ACSC	1.20 - 2.6	1.25 - 2.7
3	ACFC+AR,ARAC	5.00 - 8.90	5.10 - 9.00
4	2"AC+AR,3"AC+FC	9.20 - 11.00	9.30 - 11.20
5	4.5"AC+FC & OTHER HEAVIER ACTIONS	12.00 +	12.00 +

NOTE: The rehabilitation costs were derived based on 1990 data.

year following the application of seal coat, pavement transition follows a transition probability matrix specifically derived based on past pavement performance after the application of seal coat. The years after that year, the transition of the pavement follows the transition matrix shared by seal coat, ACFC and ACSC. Note that the new actions list does not distinguish between interstates and non-interstates, although the two have different names for some of the structural overlays. It is assumed that this assumption may not affect the budget planning based on the NOS output.

3.3.3 Roughness and Cracking Level Boundaries

The existing roughness and cracking classification levels for NOS as shown in Table 3.1 were based on the available information in the early 80's. However, the pavement performance data show these levels are no longer appropriate. For example, crack level 2 represents 11% to 30% crack in the pavement and is currently used in the NOS as the medium crack level. However, pavements at a crack level more than 10% are not in an acceptable condition state. In addition, a Maysmeter value of 90 is too rough to be considered in the good category in the interstate system, as is the case with the existing NOS system. Also, the existing classification puts a pavement at 10% crack and Maysmeter number of 80 into the best condition state, which no longer can be viewed as a good pavement by today's engineering practice. Furthermore, it is no longer valid to put interstates and non-intestates into one classification as the two roadways have different priorities and budgets.

Therefore, two sets of pavement condition state criteria are needed for interstates and non-interstates respectively. The definition of the new classifications should be based on the current pavement condition. In addition, based on the pavement design practice of ADOT, pavements with the Serviceability Indexes, SI, less than 3.0 and 2.5 are considered to be in the poor condition for interstates and non-interstates respectively. Therefore, pavements with SI's less than 3.0 and 2.5 were classified to be in high roughness category for interstates and non-interstates respectively. It is generally assumed that an interstate pavement with a SI higher than 3.5 is in good condition. Therefore, interstate pavements with SI higher than 3.5 were classified to be in the low roughness level. For the same reason, non-interstates pavements with SI higher than 3.0 were classified to be in low roughness level. Figures 3.8 to 3.11 show the correlation between the Serviceability Index and Maysmeter numbers, and histograms of pavement roughness. The figures also show the new classification ranges for both the interstates and the non-interstates.

Figures 3.12 and 3.13 represent the distribution of cracking levels for both interstates and non-interstates. The new ranges for cracking classifications were determined based on the cracking conditions of current pavement alone. Figures 3.12 to 3.13 shows that the levels of cracking classification are different for interstates and non-interstates. However, as ride quality consistently dominates the highway preservation program, the importance of determining cracking levels for both interstates and non-interstates is secondary. Based on the information given, it is determined that the following new classification levels are appropriate:

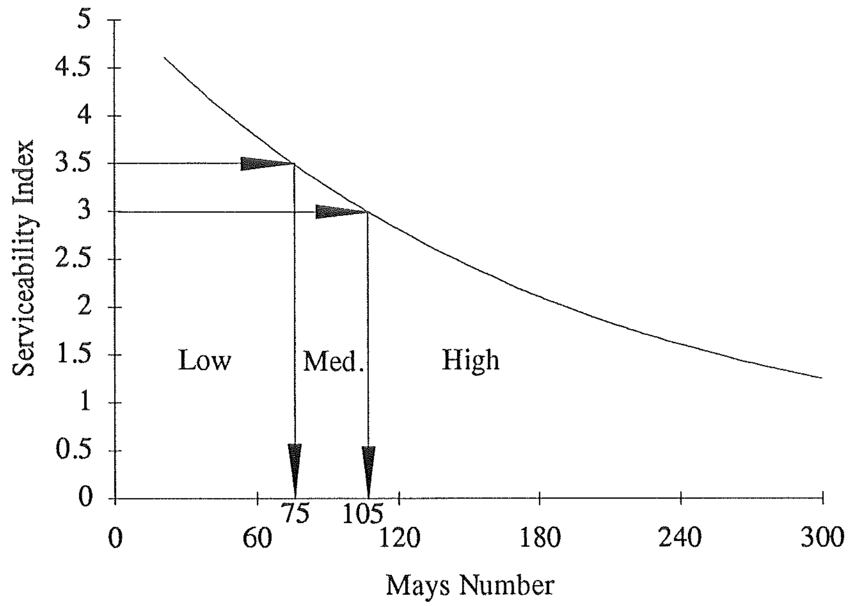


FIG. 3.8. Interstates Roughness Level Classifications

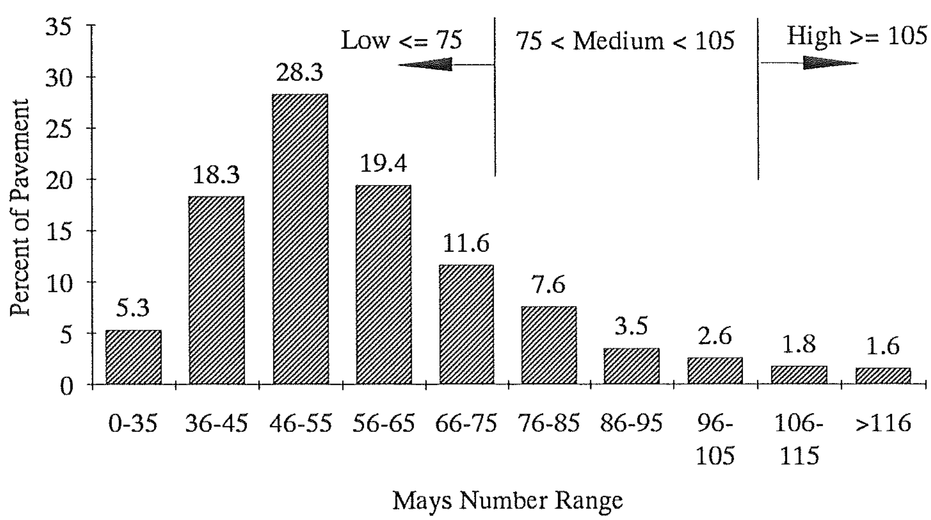


FIG. 3.9. Histogram of Interstates Roughness Distribution

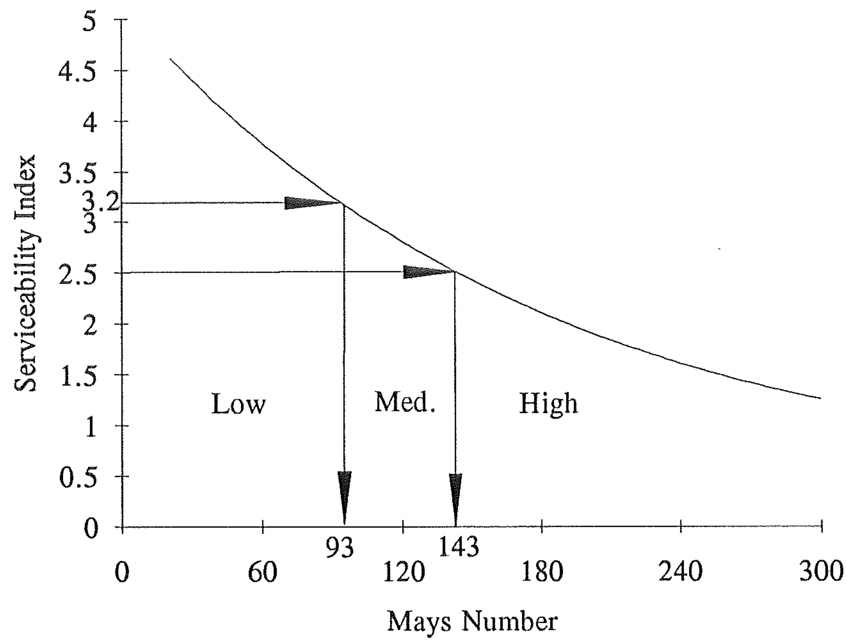


FIG. 3.10. Non-Interstates Roughness Classification Levels

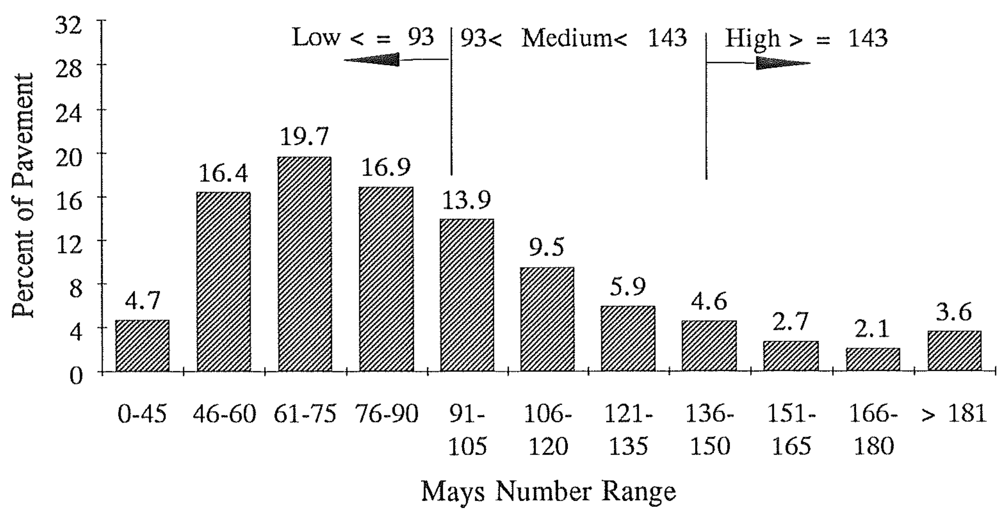


FIG. 3.11. Histogram of Non-Interstates Roughness Distribution

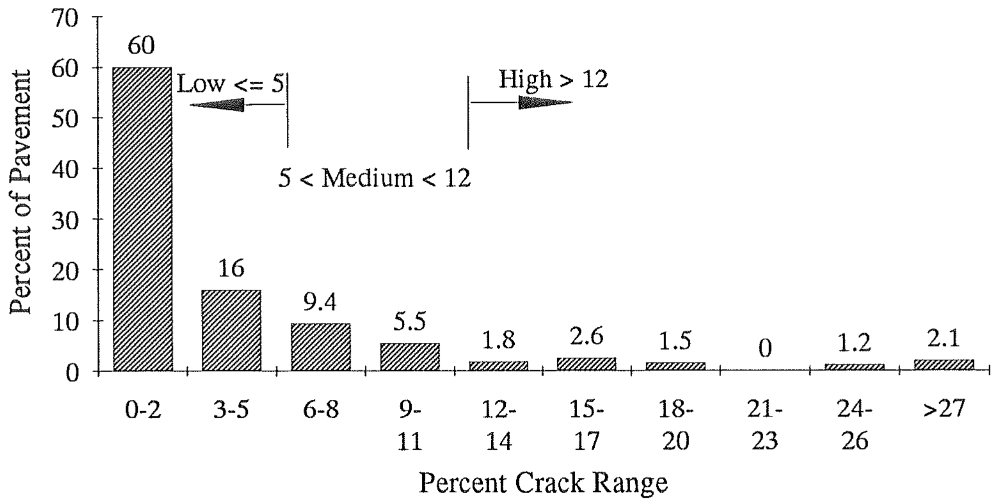


FIG. 3.12. Histogram of Intestates Cracking Level Distribution

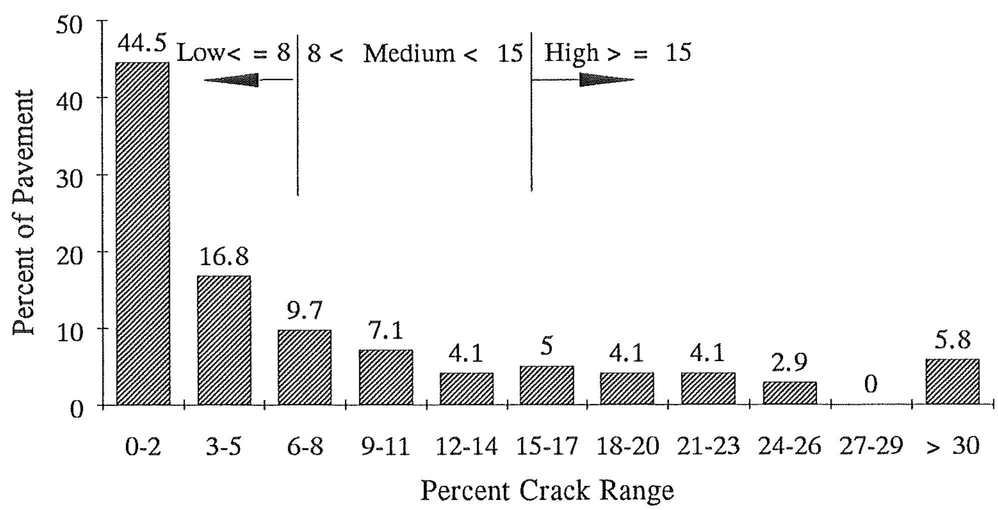


FIG. 3.13. Histogram of Non-Intestates Cracking Level Distribution

Function	Factor	Levels	Unit
Interstates	Roughness	<75, 76 - 105, >106	Maysmeter Output, inches/mile
	Cracking	0 - 5, 6 - 12, >12	percent of area
Non-Interstates	Roughness	<94, 95 - 142, >143	Maysmeter Output, inches/mile
	Cracking	0 - 8, 9 - 15, >15	percent of area

3.4 GENERATION OF TRANSITION PROBABILITIES BASED ON PERFORMANCE DATA

The transition probabilities can be obtained by observing the performance of a large number of pavements under different rehabilitation actions over a long period of time. More than ten years pavement performance data were available in 1991. The proportion of roads is computed moving from state i to j in one year, following k^{th} rehabilitation action can be determined directly. The following equation is applied to calculate the transition probability from state i to state j for each road category:

$$p_{ij}(a_k) = \frac{m_j(a_k)}{m_i(a_k)} \qquad \text{for i, j = 1,...,45, k = 1,...,6} \qquad \text{......(3.10)}$$

in which:

$p_{ij}(a_k)$ = transition probability from states i to j after action k is taken;

$m_j(a_k)$ = total number of miles where the condition states before and after the action k are i and j respectively;

$m_i(a_k)$ = total number of miles where the condition state before the action k is applied is i;

In addition, the following probability property must be observed by adjusting the biggest value among $p_{ij}(a_k)$, for j=1,...,45, and for each i and k:

$$\sum_{j=1}^{45} p_{ij}(a_k) = 1 \qquad \text{for i=1,...,45, k=1,...,6} \qquad \text{......(3.11)}$$

The newly generated transition probability matrices based on pavement performance data and equation 3.10 have been generated separately for both interstate and non-interstate highways based on the pavement performance data from 1979 to 1991.

Two sets of transition probability matrices were generated from the pavement performance data base based on the new structure of the condition states. One set was based on the original roughness and cracking levels. The second set was based on the recommended levels. The transition probabilities for remaining in the best condition under routine maintenance are shown in Tables 3.7 and 3.8 for the 15 road categories. These tables also present the number of observations used to determine the probabilities. The probabilities with small sample sizes in the tables should not be used. By examining the two tables, it is apparent that the probabilities based on the new levels are smaller than those based on the original levels. This indicates that if the current pavement performance standards are used, the pavement preservation needs will be increased due to the more stringent roughness and cracking classifications.

Transition probabilities predict future pavement condition states based on a finite-state Markov chain process. Equation 3.8 can be used to predict future pavement behavior of any number of years' horizon based on the existing one-step transition probabilities. As a result, long-term pavement probabilistic behavior can be revealed. For the sake of simplicity, P.B.C.'s were generated based on 20 years design period without consideration of rehabilitation during this period of time. Figure 3.14 shows typical pavement probabilistic behavior curves. The upper three curves starting from probability 1.0 show the proportions of pavements starting in the best condition state, remaining in the best state, the state with lowest crack level, and the state with the lowest roughness level respectively over time. The three lower curves show the proportions of pavements starting in the best condition state and transitioning to the worst condition state, the state with highest roughness level, and the state with the highest crack level respectively over time.

There are instances where the transitions do not exist in the pavement performance data files or the probability based on this transition is not representative of the real world situation due to the small sample size. In addition, the computed transition probabilities for some road categories are not representative.

It is assumed that pavement condition transitions that did not occur or occurred in only a limited number of instances in the last ten years have small probabilities to happen again. As these transitions are rarely if ever used in the optimization process, the effect on the performance prediction in NOS due to using regression-based or manually generated probabilities is small.

Therefore, in order to fulfill model requirements, the regression-based transition probabilities from the original NOS can be used in the matrices in replacement of the vacancies, the roughness and cracking levels of which are based on the original classifications. The original TPM's for 120 condition states were consolidated into TPM's with the new structure of 45 condition states. For the new matrices based on the

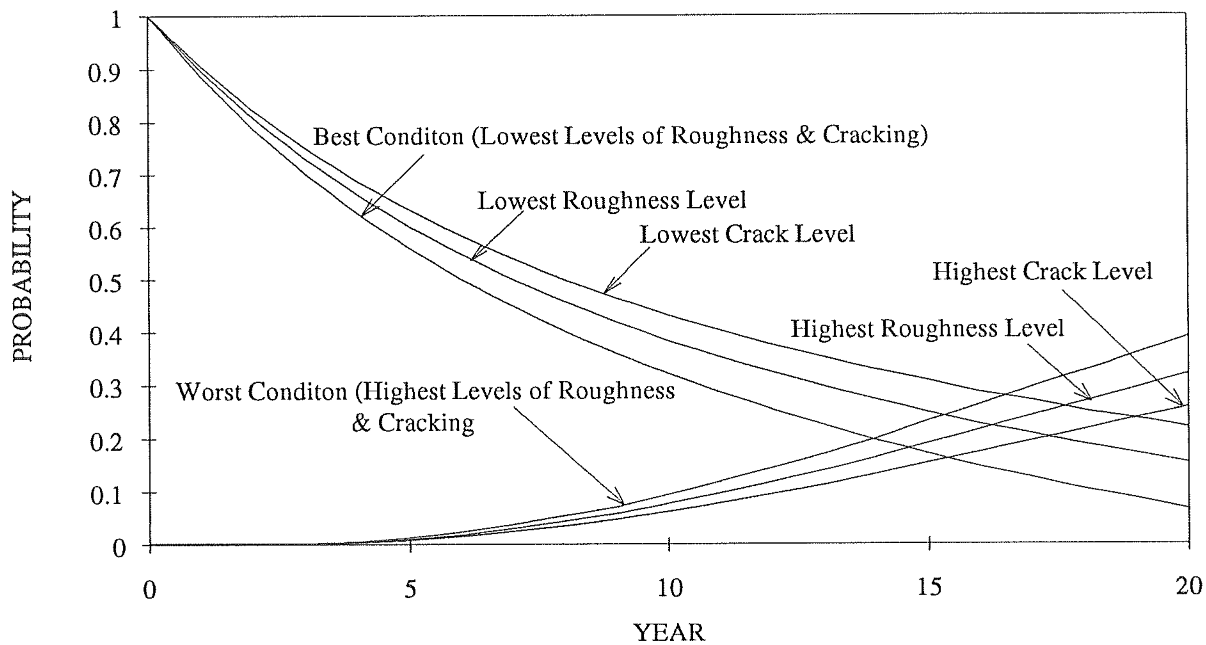


FIG. 3.14. Typical Pavement Probabilistic Behavior Curves Starting from the Best Condition State Under Routine Maintenance

TABLE 3.7. Transition Probability Comparison based on the Original Classification of Roughness and Cracking Levels

TRAFFIC LEVEL		LOW			MEDIUM			HIGH		
REGION		DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH
REHABILITATION ACTIONS / ROAD CATEGORY										
INTERSTATE	1				0.969/1635	0.990/291		0.944/2417	0.962/1922	0.912/91
	2				0.978/561	1/24		0.94/553	0.946/572	0.913/149
	3				1.0/18	N/A		01/20	N/A	0.5/2
	4				0.932/547	1/7		0.969/995	0.952/1023	1/106
	5				0.951/395	1/3		0.968/1584	0.963/835	0.993/546
NON-INTERSTATE	1	0.822/73	0.87/432	0.939/65	0.954/502	0.941/454	0.947/413	0.863/227	0.972/254	0.91/134
	2	0.967/481	.94/1107	0.91/658	0.93/1298	0.95/1465	0.944/1237	0.915/375	0.924/79	0.964/137
	3	N/A	0.963/27	N/A	0.964/139	0.921/38	0.973/73	0.986/70	N/A	N/A
	4	0.966/117	0.969/474	0.987/74	0.962/553	0.942/346	0.963/54	1.0/22	0.927/41	0.838/37
	5	N/A	0.57/7	N/A	0.956/137	1.0/4	1.0/9	1.0/5	N/A	N/A

NOTE:
The first number in the cell is the probability to stay in the best condition under routine maintenance for each rehabilitation action; the road categories do not exist for the empty cells;
The second number in the cell indicates the sample size used to compute the probability;
N/A = Sample data are not available.

TABLE 3.8. Transition Probability Comparison based on the New Classification of Roughness and Cracking Levels

TRAFFIC LEVEL		LOW			MEDIUM			HIGH		
REGION		DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH
REHABILITATION ACTIONS / ROAD CATEGORY										
INTERSTATE	1				0.91/1300	0.909/263		0.837/1890	0.855/1475	0.833/42
	2				0.919/478	0.905/21*		0.82/423	0.889/458	0.763/118
	3				1.0/16*	N/A		0.692/13*	N/A	0.5/2*
	4				0.862/435	1/7*		0.847/785	0.83/783	0.939/98
	5				0.902/325	1/3*		0.823/1172	0.893/693	0.928/499
NON-INTERSTATE	1	0.333/24*	0.771/201	0.75/32	0.857/356	0.836/317	0.718/209	0.703/121	0.869/206	0.773/88
	2	0.836/311	0.794/656	0.806/366	0.79/854	0.838/1022	0.793/834	0.741/197	0.7/50	0.707/92
	3	N/A	0.962/26*	N/A	0.958/118	0.88/25*	0.766/47	0.881/59	N/A	N/A
	4	0.581/31*	0.704/287	0.514/35*	0.869/465	0.809/236	0.923/39*	0.923/13*	0.7/20	0.143/7*
	5	N/A	N/A	N/A	0.833/102	N/A	1.0/9*	N/A	N/A	N/A

NOTE:
The first number in the cell is the probability to stay in the best condition under routine maintenance for each the rehabilitation action; the road categories do not exist for the empty cells;
The second number in the cell indicates the sample size used to compute the probability;
N/A = Sample data are not available;
* : Sample size is too small to permit the development of a reliable TPM.

new roughness and cracking levels, the approach is to use engineering judgment to fill the vacant transitions by using the transition probabilities of the road categories which have similar traffic pattern and are in adjacent geographical areas. Further analysis of this matter will be discussed in section 3.6.

3.5 ACCESSIBLE RULES

Condition state j is termed to be *accessible* from state i if $p_{ij}(a_k) > 0$. No accessibility rules for routine maintenance were established in setting up the original TPM's. As a result, an illogic situation can occur when performance predictions are made by using TPM for a pavement section in poor condition, such as state 9, high roughness and cracking based on the new structure of condition states. For example, Figure 3.15 shows 10% of pavements in the worst condition will transition to the best condition state over a period of 20-year under routine maintenance. However, in reality pavements in poor condition will not significantly improve over time under routine maintenance. In addition, the 10% improvement in Figure 3.15 is one of the factors which have attributed to the unrealistic high percentage, 55%, of pavements in the best condition state after 20 years of service.

The improvement of pavement condition states in these transitions are the results of statistical outliers and measurement variance. Low level routine maintenance applications such as crack sealing and patching can improve pavement condition only for a short period of time. Pavement deficiencies will show up in one year, or sometimes in a few months. The roughness of newly constructed or rehabilitated pavements can improve somewhat over a short period of time after construction. However, the probability approaches 1.0 for a heavy rehabilitation action producing a pavement in the best condition state as shown in Figures 3.16 and 3.17. Therefore, a slight improvement in roughness will not improve the condition state for these actions. It is recommended that the data showing pavement condition improvement under routine maintenance be discarded and accessible condition states for routine maintenance be established for the development of new matrices. Also, the pavement performance data base demonstrates pavement condition does not deteriorate two levels in one year. Accessibility rules, preventing an improvement in pavement condition and deterioration of two levels in one year, were implemented by setting their probabilities to zero. Table 3.9 shows accessible transitions based on the rules.

Figure 3.18 shows the effect of the accessibility rules for interstates with high traffic in the desert region. The accessibility rules result in a more rapid reduction in the percent of pavements in the best condition state and pavements have a somewhat higher probability of transitioning to the worst condition state over time. It is evident that during a period of 20 years, the transition pattern of the probabilistic behavior curves with the accessibility rules applied is more realistic than the curves without consideration of the rules. This is especially true for the upper curves: at the end of 20 years, the percent of pavements in best condition is predicted to be about 5% for the curve with the accessibility rules applied versus 30% for the curve without the accessibility rules. These rules were applied to the TPM's for all 15 road categories.

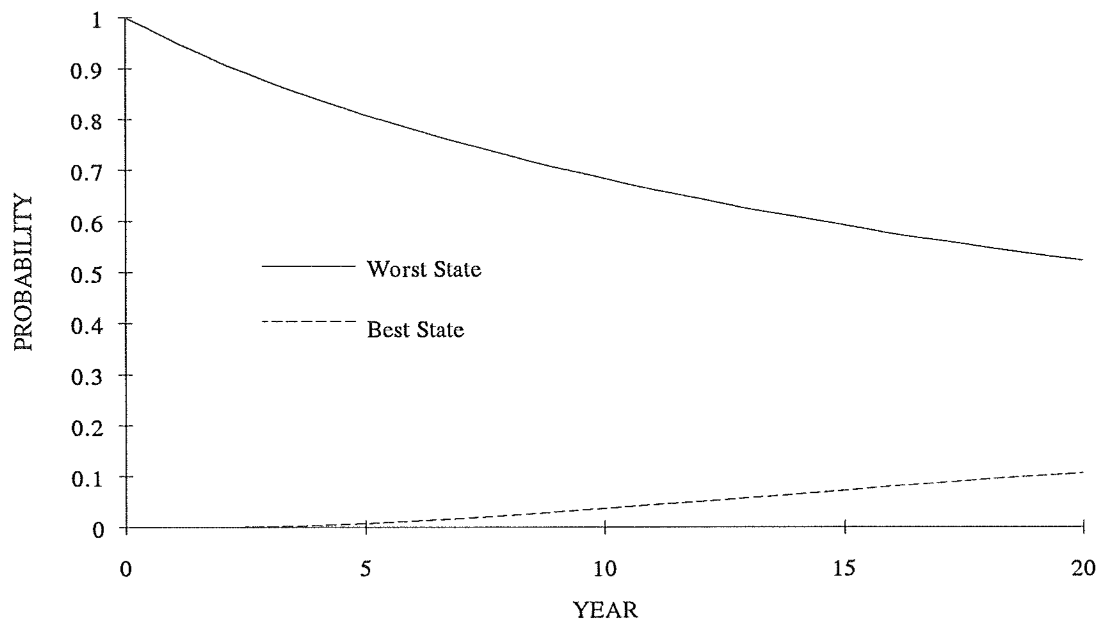


FIG. 3.15 Pavement Probabilistic Behavior Curves Starting from the Worst Condition State under Routine Maintenance, Medium Traffic Interstates in Desert Region, Based on the Original Matrix with 120 Condition States

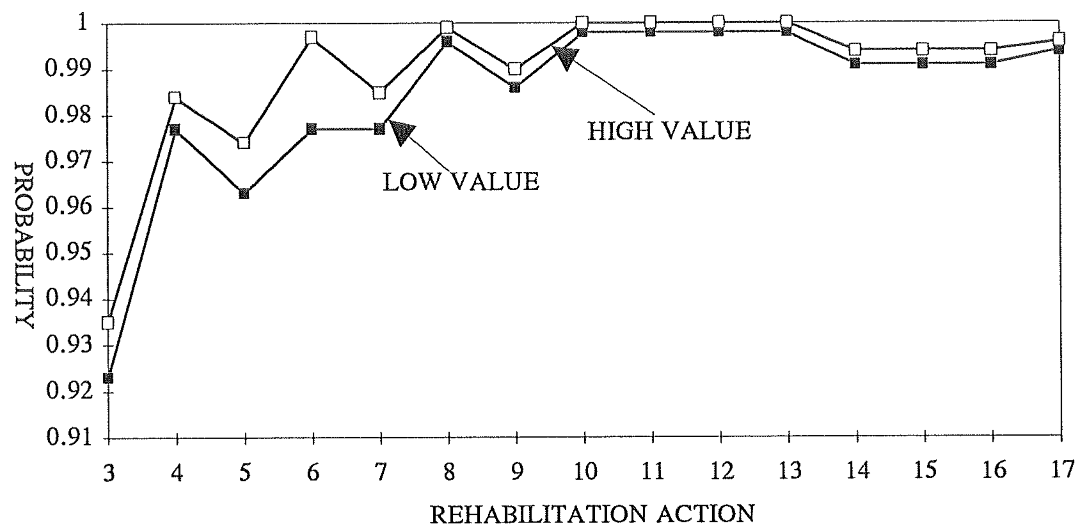


FIGURE 3.16. Probabilities to Transform the Pavement to the Best Condition State by the 15 Rehabilitation Actions, Interstates

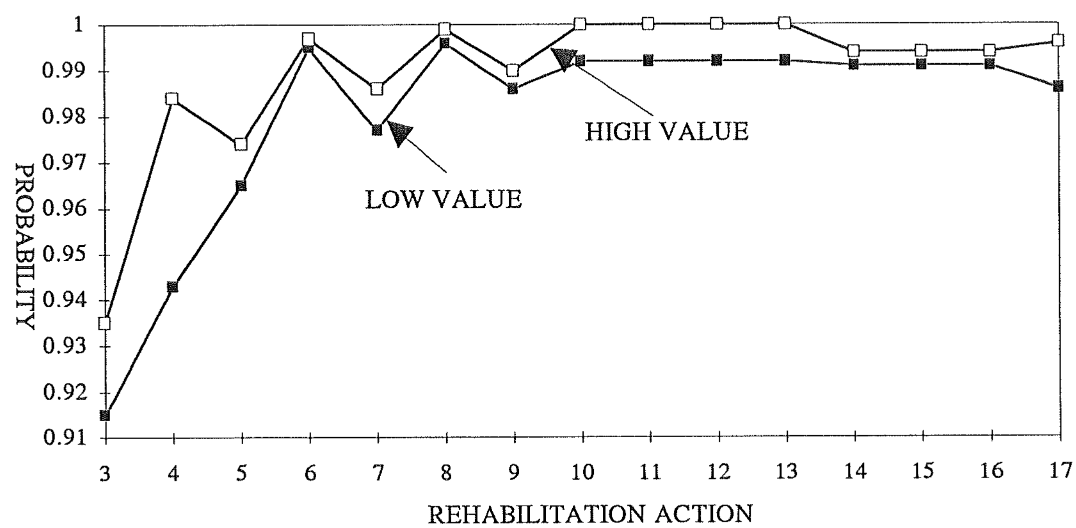


FIGURE 3.17. Probabilities to Transform the Pavement to the Best Condition State by the 15 Rehabilitation Actions, Non-Interstates

* : The transition probabilities, $P_{ij}(a_k)$, in the Figures represent the one major transition from i (i=1,...45) to j (j=1,or 10,or 19,or 28, or 37) under action 3 to 17.

TABLE 3.9. Accessibility Table for the 45 Condition States under Routine Maintenance

FROM	TO				FROM	TO			
1	1	2	4	5	24	24	27		
2	2	3	5	6	25	25	26		
3	3	6			26	26	27		
4	4	5	7	8	27	27			
5	5	6	8	9	28	28	29	31	32
6	6	9			29	29	30	32	33
7	7	8			30	30	33		
8	8	9			31	31	32	34	35
9	9				32	32	33	35	36
10	10	11	13	14	33	33	36		
11	11	12	14	15	34	34	35		
12	12	15			35	35	36		
13	13	14	16	17	36	36			
14	14	15	17	18	37	37	38	40	41
15	15	18			38	38	39	41	42
16	16	17			39	39	42		
17	17	18			40	40	41	43	44
18	18				41	41	42	44	45
19	19	20	22	23	42	42	45		
20	20	21	23	24	43	43	44		
21	21	24			44	44	45		
22	22	23	25	26	45	45			
23	23	24	26	27					

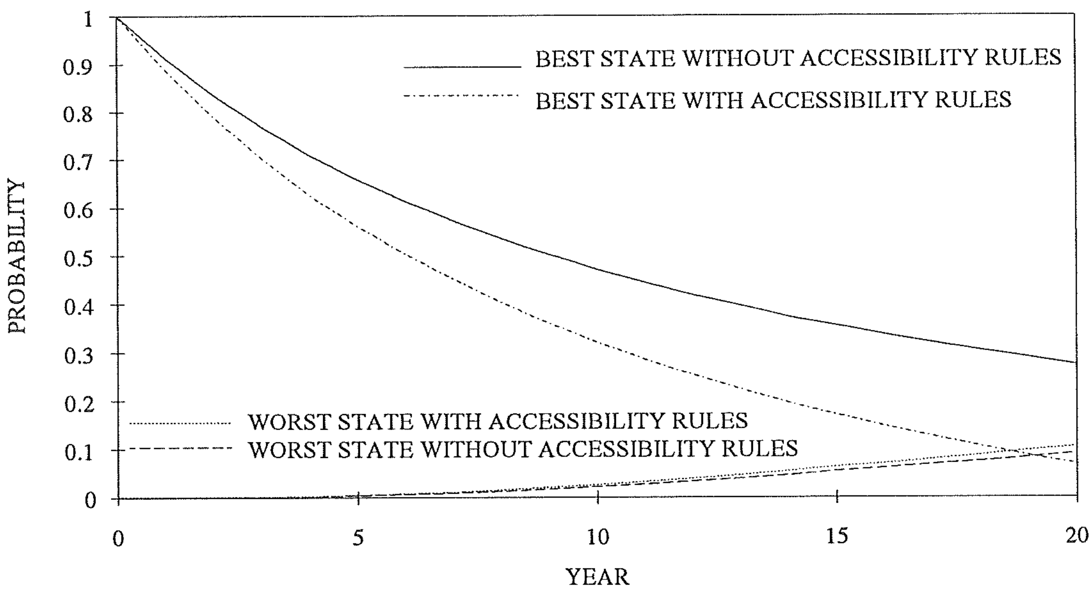


FIG. 3.18. Pavement Probabilistic Behavior Curves Starting from the Best Condition State under Routine Maintenance after the Application of 3' AC plus FC, High Traffic Road Category of Interstates in Desert Region, Based on the TPM with 45 Condition States.

3.6 FURTHER ANALYSIS OF PAVEMENT PROBABILISTIC BEHAVIOR

The Markov process is a powerful tool to predict pavement behavior. However, this prediction was based on the prediction model set up with past pavement performance data in Arizona. Further analysis is necessary to validate the models for each road category.

3.6.1 Examination of the TPM's Validity

The reliability of pavement performance prediction is crucial to the successful implementation of any pavement management system. In the case of NOS, as the roughness standards set by the department are in the range of 0.85 to 0.95 for the Interstates, the values of major transition probabilities to remain in the best condition state greatly affect the budgetary needs of the highway preservation program when the rehabilitation costs are fixed. To a great extent, these values also represent the deterioration tendencies of various pavements under consideration. The closer to 1.0 the values are, the less budget needs will be reported by NOS.

However, some of the newly generated TPM's based on pavement performance data do not realistically represent the pavement performance during a period of 20 year's horizon as shown in Figures 3.19 to 3.24. All these probabilistic behavior curves are based on newly generated TPM's at the new roughness and cracking levels as classified in section 3.3.3.

The legend in the figures are defined as the following. *Best State* is the probability over time for a pavement to stay in the best condition, percent of crack<9, Maysmeter number<75 for the Intestates and <94 for the Non-Interstates. *Worst State* is defined as the probability in the worst condition over time, percent of crack>12, Maysmeter number>106 for the Interstates and >143 for the Non-Interstates. *Best Ride* is the probability roughness remains less than 75 for the Interstates and less than 94 for the Non-Interstates. *Worst Ride* is the probability roughness is larger than 105 for the Interstates and larger than 143 for the Non-Interstates. *Best Crack* is the probability the percent crack remains less than 9%. *Worst Crack* is the probability the percent of crack is larger than 18%. These 6 parameters are used here to analyze the full spectrum of pavement long-term probabilistic behavior.

It is reasonable to assume under the new classifications of roughness and cracking, the condition of pavements will transition such that only a very small percent of the pavements will be still in the best condition state after 20 years' service. In Figures 3.19 through 3.24, 20% to 40% of the pavements are in the best condition state after 20 years' service. Therefore, the TPM's for the related road categories and action groups can not be used in NOS.

There can be many factors which account for this unrealistic behavior illustrated in Figures 3.19 to 3.24. However, identifying factors responsible for the unrealistic behavior is not possible with the available data. Nevertheless, the application of Markovain process allows easy manual intervention with the transition

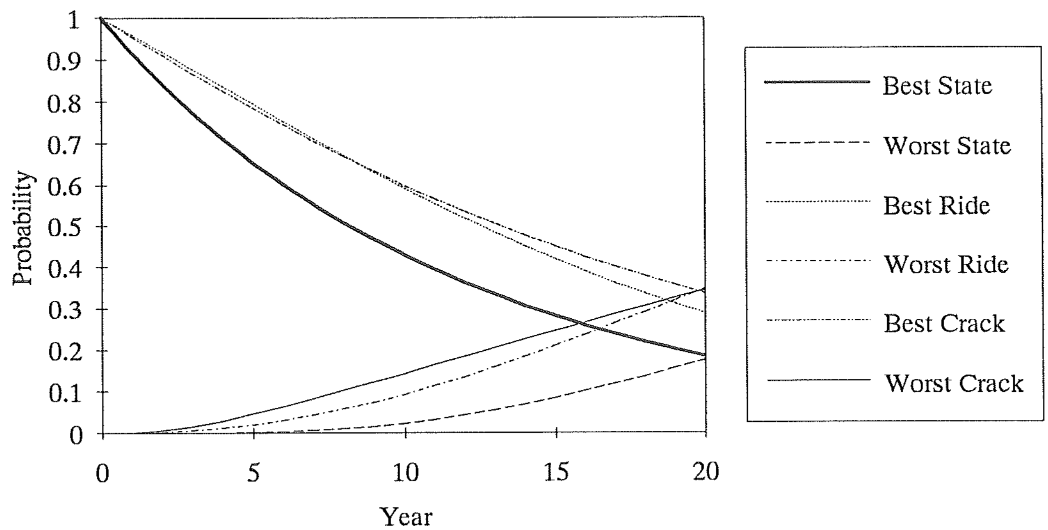


FIG. 3.19. Pavement Probabilistic Behavior Curves under Routine Maintenance After New Construction, Medium Traffic Road Category of Interstates in Desert Region

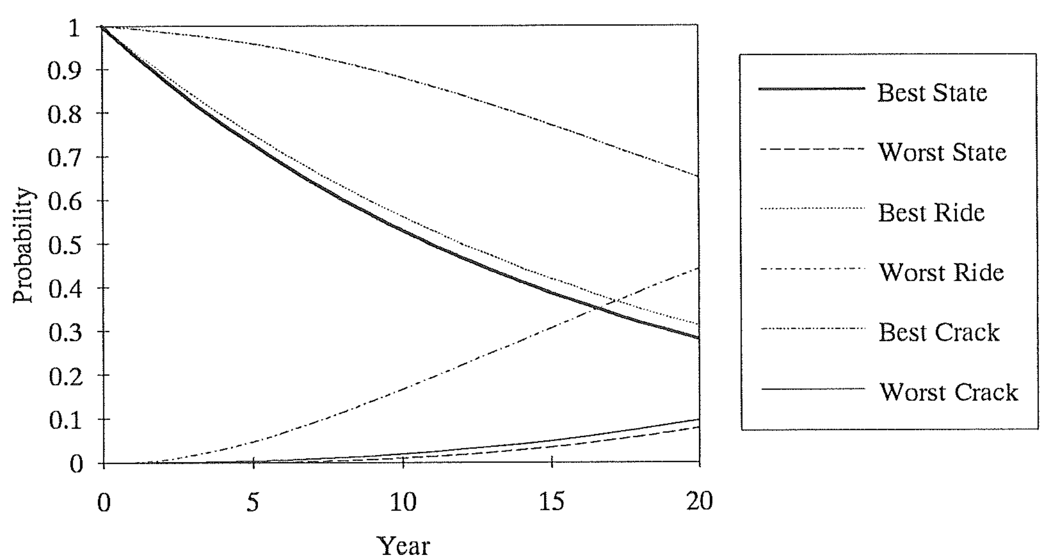


FIG. 3.20. Pavement Probabilistic Behavior Curves under Routine Maintenance After a Surface Application, Medium Traffic Road Category of Interstates in Desert Region

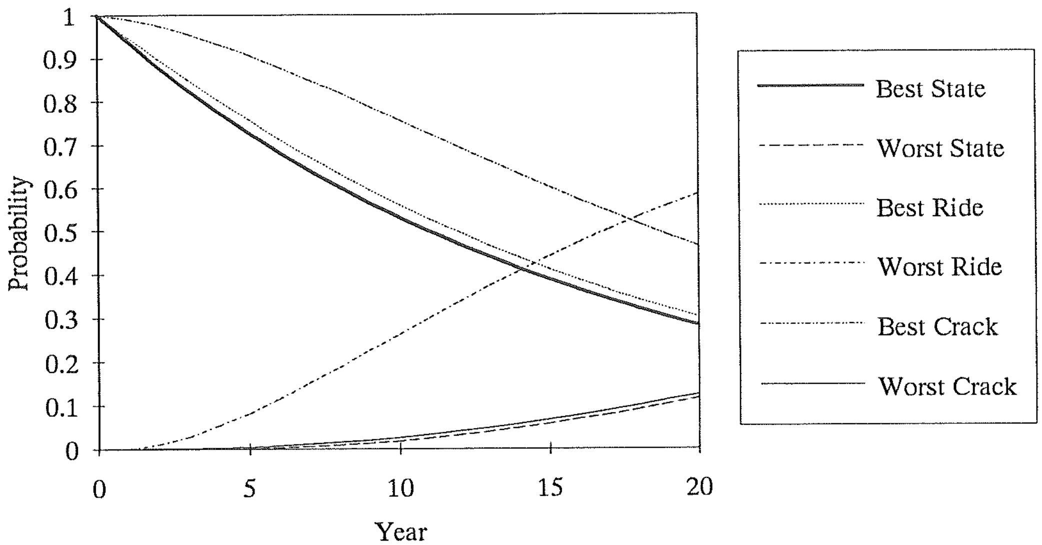


FIG. 3.21. Pavement Probabilistic Behavior Curves under Routine Maintenance After a 3"AC plus FC, High Traffic Road Category of Interstates in Mountain Region

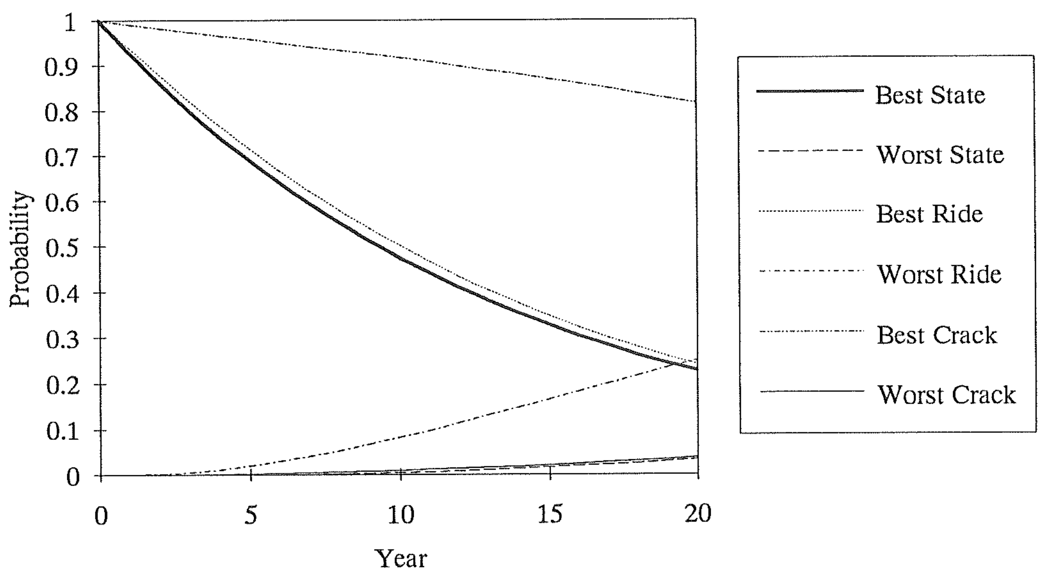


FIG. 3.22. Pavement Probabilistic Behavior Curves under Routine Maintenanc After a 5"AC plus FC, High Traffic Road Category of Interstates in Mountain Region

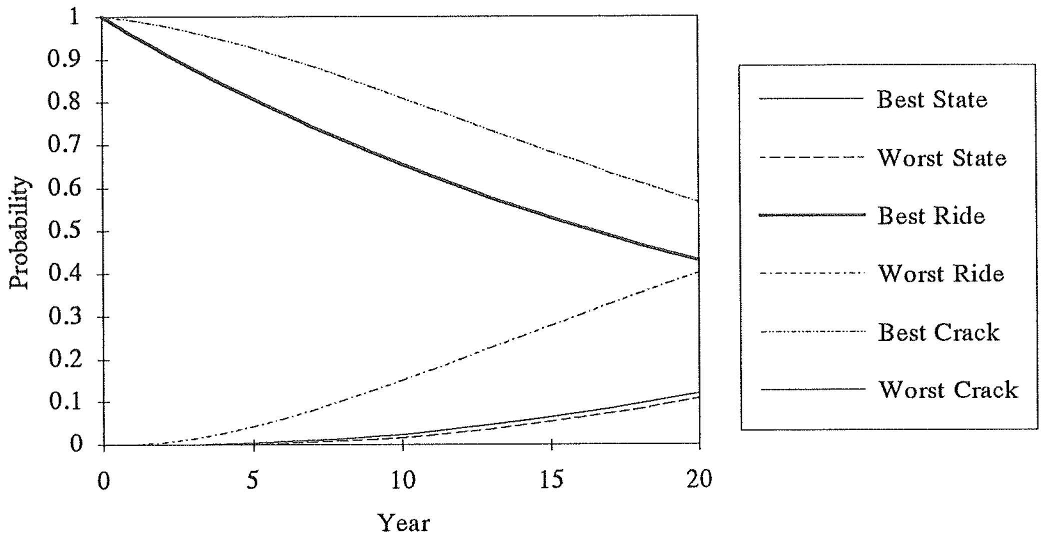


FIG. 3.23. Pavement Probabilistic Behavior Curves under Routine Maintenance After an ACFC Application, Medium Traffic Road Category of Non-Interstates in Transition Region

Note: The curves for *Best State* and *Best Ride* share the same set of data points.

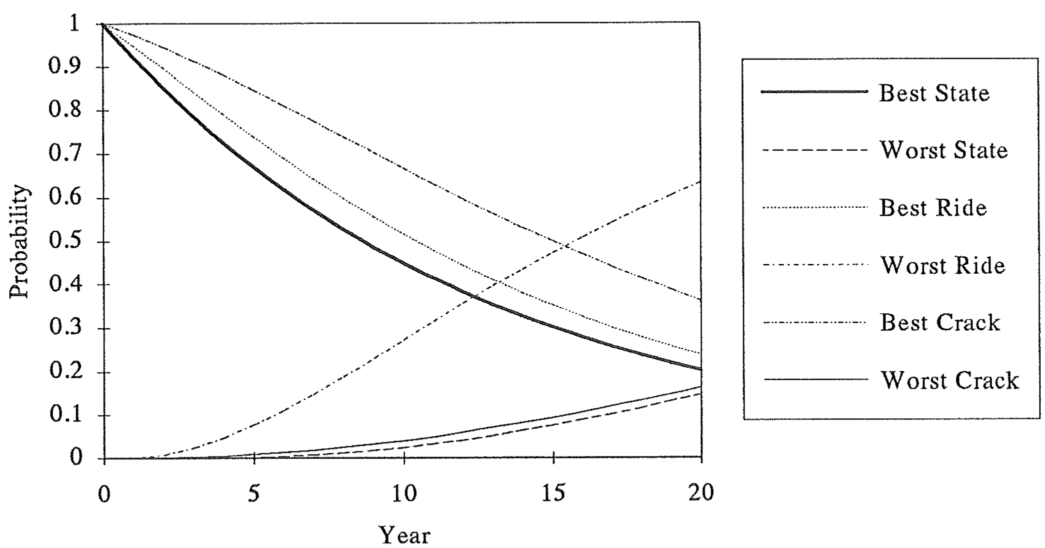


FIG. 3.24. Pavement Probabilistic Behavior Curves under Routine Maintenance After an ACFC Application, Medium Traffic Road Category of Non-Interstates in Mountain Region

probabilities. When no actual pavement behavior data were available, subjective opinions from experienced engineers were used to develop TPM's (FHWA, 1991). Also in 1985 engineering judgment was used to update TPM's of the ADOT NOS. Therefore, the data used to generate the TPM's for the six road categories have to be discarded and subjective measures need to be used to obtain the new TPM's.

Fortunately, a number of TPM's exhibit rational behavior as shown in Figures 3.25 to 3.28. It can be seen from these four figures that the percent of pavements remaining in the best condition state after 20 years' service is approximately 5%. The curves of *best ride* and *worst ride* demonstrates the rapid deterioration of riding quality over time consistently for all four figures. The deterioration of pavement structural quality is much slower than ride as evidenced by the curves of *best crack* and *worst crack*. These observations conforms to the conclusion made in previous sections and statements as published in the *AASHTO Guide for Design of Pavement Structures* (see 3.3.1). It is interesting to note that the patterns of curves for ride and crack in Figures 3.19 to 3.24 are very similar to the ones in Figures 3.25 to 3.28.

Based on the analysis of pavement long-term probabilistic behavior of all TPM's, there are a total of 33 TPM's which can be used as shown in highlighted cells in Table 3.10. From Table 3.8, there are a total of 18 cells whose sample sizes are too small to permit the development of reliable TPM's. Thus, the data in these 18 cells were not used. However, there is one cell in Table 3.8 with the sample size of 32 which produces a reasonable P.B.C., representing low traffic, mountain region of the Non-Interstates under routine maintenance. Therefore, the data for this cell were used even though the sample size is smaller than desired. In addition, there are empty 13 cells labeled N/A in Table 3.8 where no data were available. Finally, a total of 5 cells underlined in Table 3.10 were inappropriate to be used for performance prediction based on the observation of their P.B.C.'s. Therefore, the data for the five TPM's had to be discarded.

It can be assumed that TPM's of road categories with adjacent traffic levels/geographical regions, and with adjacent action groups have similar properties. Therefore, the valid 33 TPM's can be used in the 37 TPM's where the data were either unavailable, the sample size too small, or their P.B.C.'s were not realistic. However, in order to reduce error, this filling process can only take place within interstates or non-interstates as the two types of highways have distinct transition probabilities as shown by the probability values of the major transitioning of staying in the best condition state in Table 3.8. The complete set of TPM's under routine maintenance for the 14 road categories are shown in Appendix A. As there are no pavements in road category of medium traffic, mountain region, the TPM's for this road category are not available.

3.6.2 Pavement Behavior and Markovian Prediction

The prediction model setup is demonstrated in section 2.4.3. Although the Markovain prediction model is an integral component for NOS optimization, the prediction model itself can also be used to examine future pavement behavior as shown by equation 3.8.

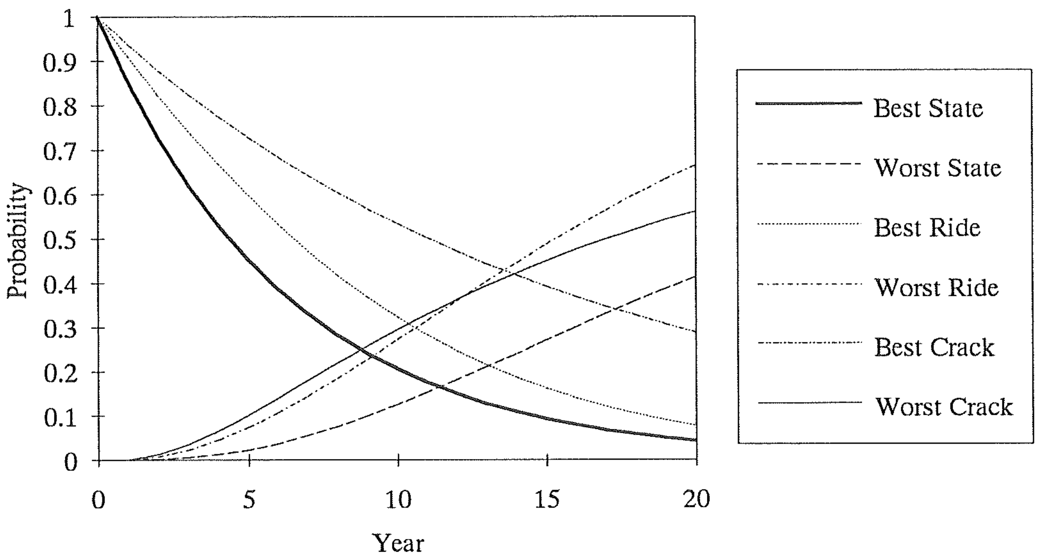


FIG. 3.25. Pavement Probabilistic Behavior Curves under Routine Maintenance After New Construction, High Traffic Road Category of Interstates in Desert Region

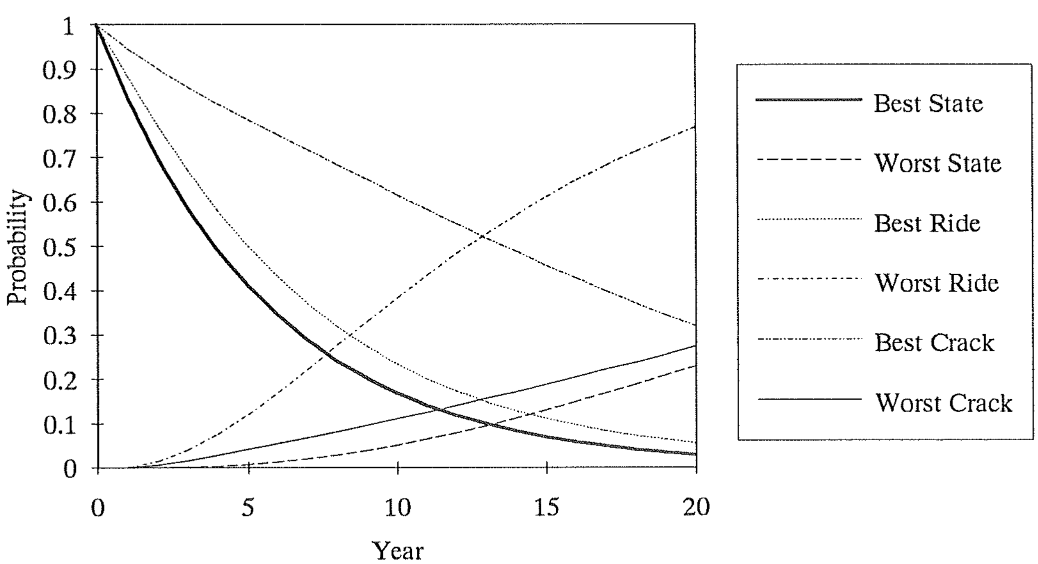


FIG. 3.26. Pavement Probabilistic Behavior Curves under Routine Maintenance After a Surface Application, High Traffic Road Category of Interstates in Desert Region

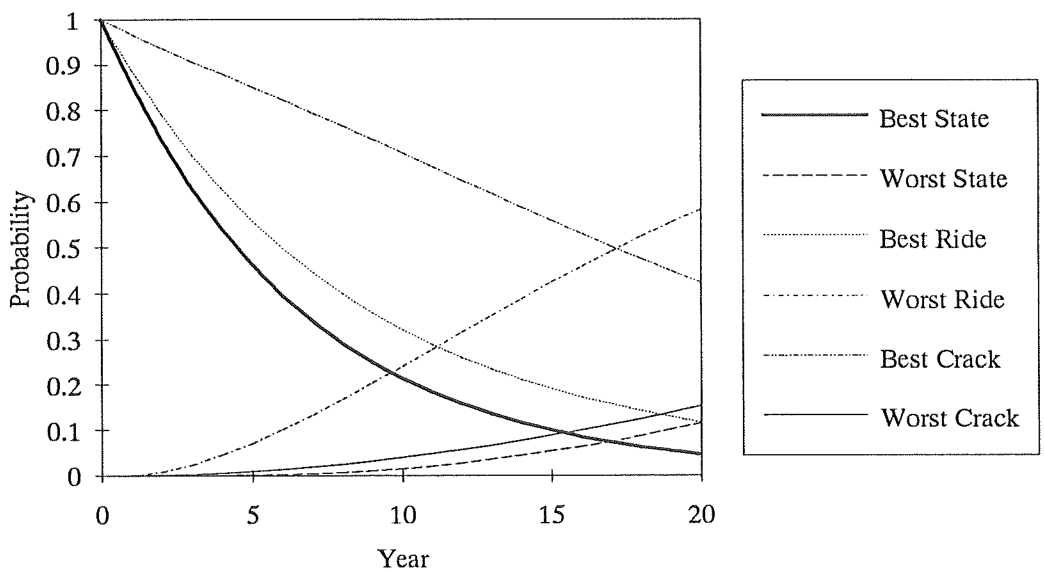


FIG. 3.27. Pavement Probabilistic Behavior Curves under Routine Maintenance After a 3" AC plus FC, High Traffic Road Category of Interstates in Desert Region

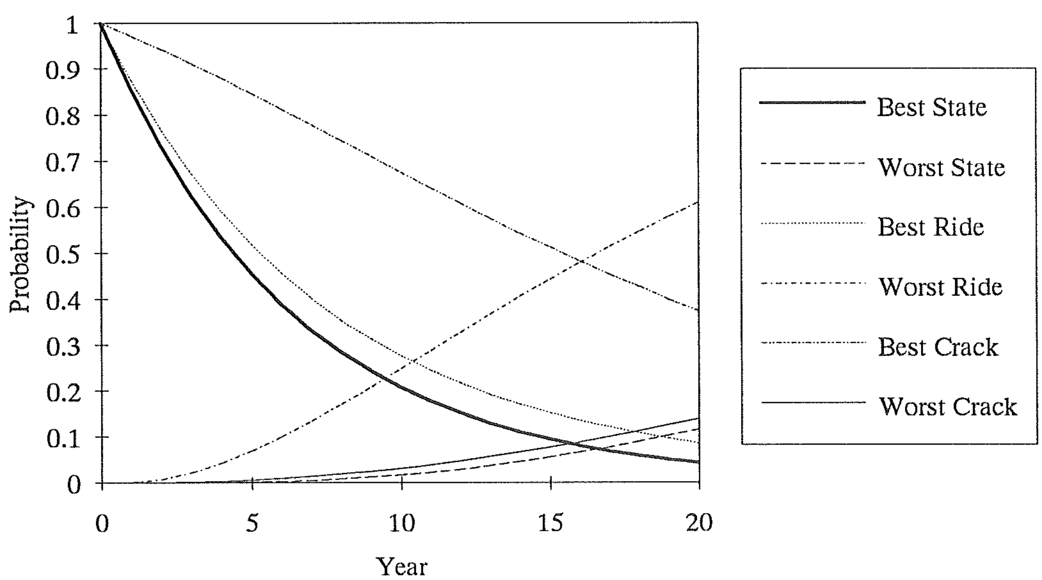


FIG. 3.28. Pavement Probabilistic Behavior Curves under Routine Maintenance After a 5" AC plus FC, High Traffic Road Category of Interstates in Desert Region

TABLE 3.10. Filling of Transition Probability Matrices Based on Valid Adjacent Matrices

TRAFFIC LEVEL		LOW			MEDIUM			HIGH		
REGION		DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH
REHABILITATION ACTIONS / ROAD CATEGORY										
INTERSTATE	1				<u>31I-1</u>	<u>32I-1</u>		**0.837/1890**	**0.855/1475**	**0.833/42**
	2				<u>31I-2</u>	32I-2*		**0.82/423**	**0.889/458**	**0.763/118**
	3				31I-4*	32I-4***		31I-4*	31I-4***	32I-4*
	4				**0.862/435**	32I-4*		**0.847/785**	**0.83/783**	32I-4*
	5				**0.902/325**	32I-5*		**0.823/1172**	**0.893/693**	<u>32I-5</u>
NON-INTERSTATE	1	12N-1*	**0.771/201**	**0.75/32****	**0.857/356**	**0.836/317**	**0.718/209**	**0.703/121**	**0.869/206**	**0.773/88**
	2	**0.836/311**	**0.794/656**	**0.806/366**	**0.79/854**	**0.838/1022**	**0.793/834**	**0.741/197**	31N-2*	**0.707/92**
	3	11N-2***	12N-2*	23N-3***	<u>21N-2</u>	22N-2*	**0.766/47**	**0.881/59**	21N-3***	23N-3***
	4	12N-4*	**0.704/287**	12N-4*	**0.869/465**	**0.809/236**	22N-4*	21N-4*	22N-4*	22N-4*
	5	21N-5***	12N-4***	12N-4***	**0.833/102**	22N-4***	22N-4*	21N-5***	22N-4***	22N-4***

NOTE:
The code in the cell being filled represents the location of TPM used for the current cell. The first digit of the code is the traffic level, the second digit it the region level, the letter following the two digits represent interstates (I) or non-interstatets (N), the last digit is the number for one of the five the action group; The digits of 1,2,3 used in the code represent low traffic, medium traffic, and high traffic; or desert region, transition region, or mountain region respectively; The road categories do not exist for the empty cells;

* means the cell originally had small sample size;

** means the data of this cell is used even though the sample size is less than desirable;

*** means the cells originally did not have any data or N/A as shown in Figure 3.8.

The newly generated TPM's were used to predict pavement condition states. Figures 3.29 and 3.30 show the predictions of percentages of pavements in the best and worst condition states for pavements starting from the condition states of 1991. The best condition state has the low levels of roughness and cracking while the worst condition state has the high levels of roughness and cracking. The figures show that the curves representing the condition transitions during the first year are not as smooth as shown in Figures 3.25 to 3.28. This abrupt change of percentages of pavements in the two condition states is largely due to the existence of various current condition states which affect the first year's transitions. In Figure 3.25 to 3.28, the pavement condition was assumed to be 100% in the best condition at year 0. Therefore, the transition patterns were determined by the TPM's alone. As in the case of actual prediction as shown in Figures 3.29 and 3.30, pavements started from the current condition vector which contains more than one condition state. This explanation is illustrated by the following equation:

$$[1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]\cdot\begin{bmatrix} .85 & .06 & 0 & .08 & .01 & 0 & 0 & 0 & 0 \\ x & x & x & x & x & x & x & x & x \\ x & x & x & x & x & x & x & x & x \\ x & x & x & x & x & x & x & x & x \\ x & x & x & x & x & x & x & x & x \\ x & x & x & x & x & x & x & x & x \\ x & x & x & x & x & x & x & x & x \\ x & x & x & x & x & x & x & x & x \\ x & x & x & x & x & x & x & x & x \end{bmatrix} = [0.85\ .06\ 0\ .08\ .01\ 0\ 0\ 0\ 0]$$

......(3.11)

Equation 3.11 demonstrates a first year condition transition with 9 condition states, where all the pavements in the best condition state is represented by the initial vector [1 0 0 0 0 0 0 0 0]. The values of x's can be any numbers conforming to the probability definition as they do not affect the result from this matrix multiplication. From equation 3.11, the pavement condition vector after this transition is the first row of the TPM. Therefore, the transition pattern is determined by the TPM alone when the initial pavement conditions are 100% in condition state one. When the initial condition vector is anything other than 100% best, the smooth transition from year 0 to year 1 is not guaranteed. However, the effect of the initial condition states is dispersed by the multiplications of TPM's as shown in Figures 3.29 to 3.30.

To validate the Markovian prediction based on the new TPM's, the prediction made by the model and pavement behavior under routine maintenance were illustrated in Figure 3.31 for high traffic, desert region interstates. The pavement behavior curve shown in Figure 3.31 represents the percent of pavements in the best condition state. This curve was generated based on actual pavement performance data. Pavement condition data of every year in the data base were used as long as the pavements were under routine maintenance since 1979 to 1990. Whenever a pavement was rehabilitated or showed improvement in both roughness and cracking, the data on this pavement in the following years were not used.

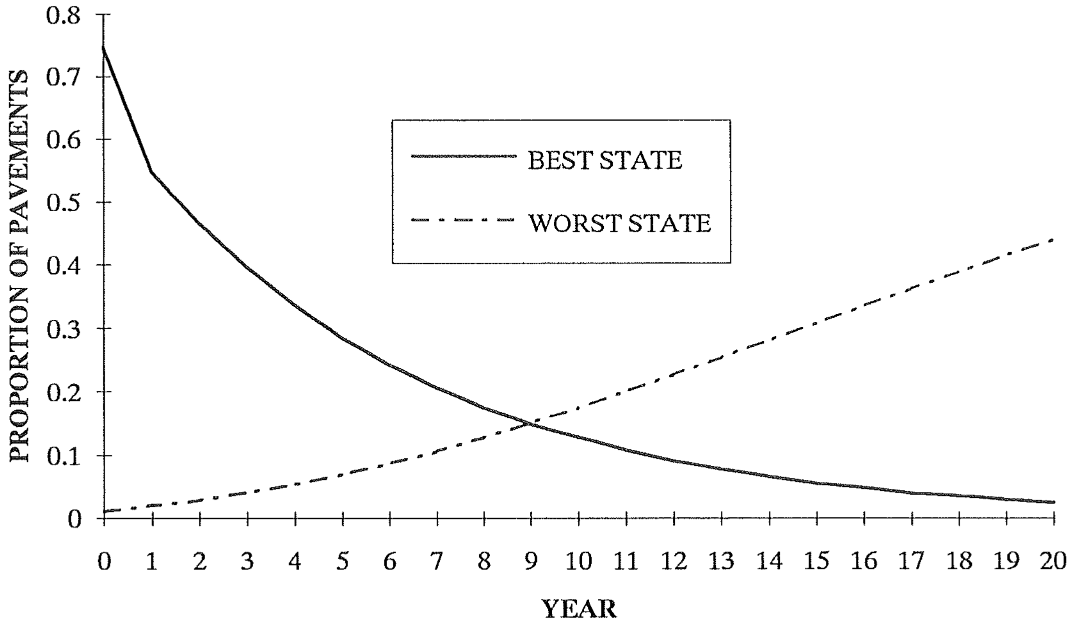


FIG. 3.29. Pavement Condition Prediction for High Traffic, Desert Region, Interstates

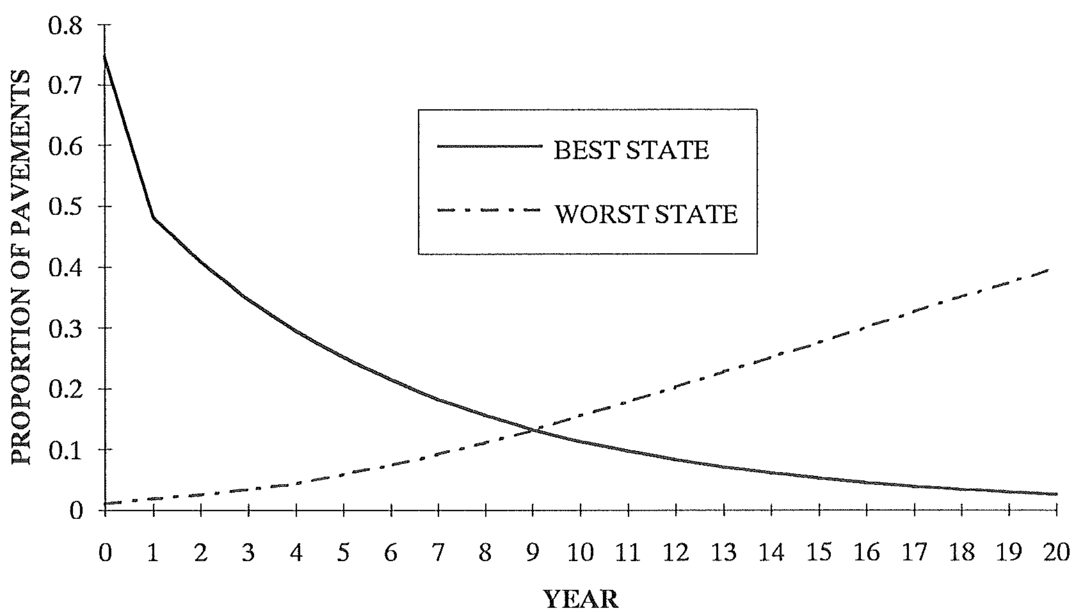


FIG. 3.30. Pavement Condition Prediction for Medium Traffic, Desert Region, Non-Interstates

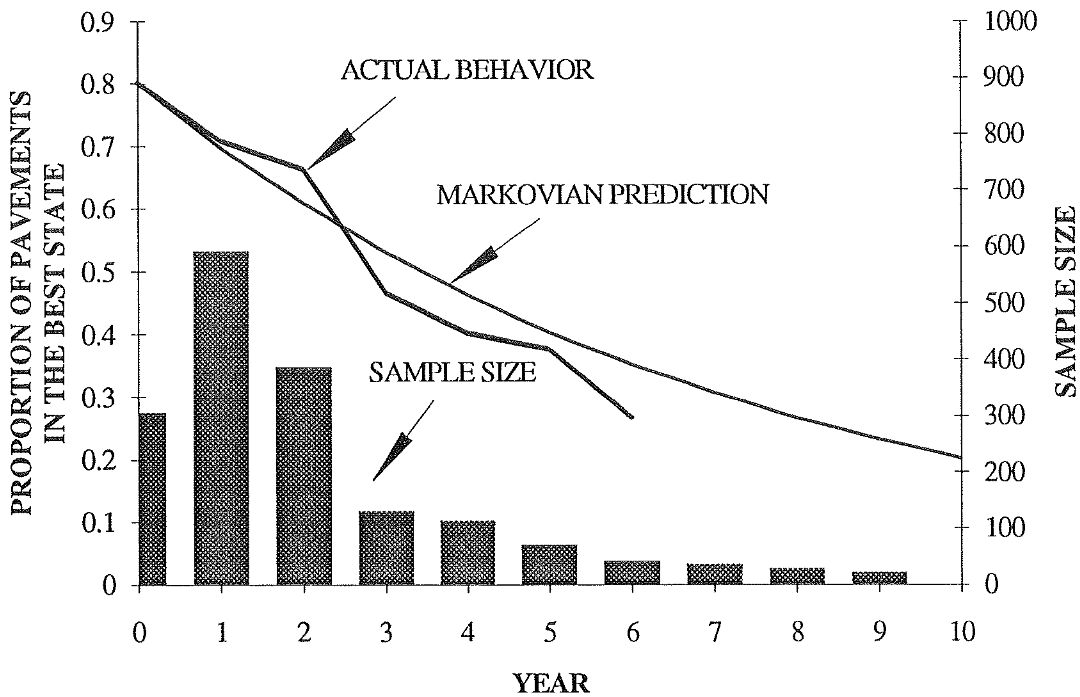


FIG. 3.31. Pavement Behavior and Markovian Prediction, Interstates of High Traffic, Transition Region.

It can be seen from Figure 3.31 that the fit of actual pavement behavior and Markovian prediction was good. Figure 3.31 also shows the number of samples that were available for plotting the actual pavement probabilistic behavior curves. The number of samples represent the number of miles which were used to the computation. The sample sizes decreased with time when more and more pavements showed improvement in their levels of roughness and cracking. Appendix B includes 12 figures which demonstrate the prediction and actual behavior of pavements for the 12 road categories. Most of the comparisons show good fitness for the two curves. The sample sizes for two of the road categories were too small to be meaningful. Therefore, their curves were not shown in Appendix B. As there are no pavements for road category of interstates with medium traffic in the mountain region, the corresponding figure is not available.

3.8 CONCLUSION

Two approaches were used to evaluate the TPM's in this chapter. First, the current pavement performance data base was used to develop new TPM's. Second, the Chapman-Kolmogorov method was used to examine the logical extension of the transition probability matrices from a single step to the long term pavement performance behavior. As a result, the concept of pavement probabilistic behavior curve, P.B.C., is established based on the Chapman-Kolmogorov equations. Both the old TPM's and the new TPM's based on pavement performance database were evaluated in this chapter. By applying Chapman-Kolmogorov equations, 5 TPM's were determined invalid for long-term pavement performance prediction in NOS. Thirty-three TPM's were used to fill in the vacant transitions of the 37 TPM's where either data were unavailable, the sample sizes were too small, or their P.B.C.'s were not realistic. The effect of crack change in predicting pavement deterioration is analyzed in this chapter based on past pavement performance data. Analysis is also conducted on the validity of using 17 rehabilitation actions in the model.

It was revealed in this study that the factor of crack change is not significant in determining the acceleration of pavement deterioration in Arizona. Therefore, this factor was removed from the system. A new structure of pavement condition states was set up for the optimization model. The number of condition states was reduced from 120 to 45 and the number of rehabilitation actions was reduced from 17 to 6. New TPM's were established for both the interstates and non-interstates based on the 13-year's pavement performance data base in Arizona. The TPM's were modified with accessibility rules to improve the prediction of pavement performance. Furthermore, the prediction model developed based on Markov process was used to predict pavement condition states for the road categories. It was revealed that the fitness of actual pavement behavior and Markovian prediction was satisfactory. As new analysis tools and past pavement behavior data were carefully used to make these enhancements, the developments conducted in this chapter will improve the reliability and computation efficiency of the NOS.